SPATIAL VARIATIONS IN EOLIAN STRATIGRAPHIC ARCHITECTURE OF THE NORPHLET FORMATION, SOUTHWESTERN ALABAMA

A Thesis

by

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ABSTRACT

In modern eolian dune fields, dune-field patterns arise from the autogenic behavior of dunes and the external environmental conditions within these interactions operate. When autogenic behaviors alone are considered, a generic pattern emerges with little variability in the pattern but much spatial variability arises as a dune-field pattern emerges within a set of boundary conditions. One way in which this variability is expressed in modern dune fields is by an increase in crest line spacing and decrease of defect density away from a sand source area. To determine if this dune pattern behavior is apparent in the eolian rock record, we studied the Upper Jurassic Norphlet Formation with the aim of inferring the stratigraphic configuration of a limited area, based on the detailed facies analysis and their vertical and lateral variations from three cores recovered at increasing distance from inferred upland source areas. Detailed facies interpretation was performed and eolian set and grainflow thickness were measured in three cores. Results indicate that spatial and temporal depositional changes occurred in the system during Norphlet Formation deposition, evidenced by lateral facies variability from fluvial-eolian to mainly eolian deposition in the erg center. Facies identified include interdune, wadi, eolian dune, sandsheet and marine facies. Spatially the dune field transitioned from a fluvially dominated margin with small eolian sets to an eolian dominated dune-field center with the thickest overall sets. An increase in set thickness and decrease in the total number of first order bounding surfaces moving away from the sediment source were identified, with set thickness ranging between 1 to 6 m in the erg center. Preserved grainflow thickness shows a positive correlation with distance from the sediment paleosource, with a significant population between 0.5 and 1.6 cm thick for the middle and distal locations.

Temporal changes transitioned upward from wet interdune strata to wadi and dry dune facies, to an interval of sandsheets that grades to marine deposits. Foreset strata orientation from dipmeters indicates scatter bedding directions for the updip location but a narrower distribution in Hatters Pond (SW) and Mobile Bay (SE-E), suggesting these as the prevailing wind directions in those areas. The succession implies a relative sea level rise at the end of the Norphlet deposition. Interpreted climatic conditions suggest a wetter fluvio-eolian system prevailed in the updip location that changed to a dryer dune dominated area in the dune field center. The transition to the uppermost Norphlet section characterized by sandsheets and marine siltstones, indicates a combination of decrease in sediment availability, increase in sea level, and increase in water table level, leading to cessation of eolian deposition.

DEDICATION

To my family for their unconditional love and support and to Juan Carlos for encouraging me to continue my academic education and starting this new life overseas together.

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NOMENCLATURE

BS	Bounding Surface
Cm	Centimeters
E	East
ED	Eolian dune facies association
EGOM	Eastern Gulf of Mexico
EI	Interdune facies association
ES	Sandsheets facies association
FE	Fluvial (wadi) facies association
Ft	Feet
GCM 35-11-2	Well Getty Creola Minerals 35-11-2
GOM	Gulf of Mexico
HP-16-9-1	Well Hatters Pond 16-9-1
Km	Kilometer
M	Marine facies association
M	Meters
N	North
NE	Northeast
PGU-19-4	Well Powell Gas Unit 19-4
S	South
SE	Southeast
STL-350-95-3	Well State Lease 350-95-3
STL-9597	Well State Lease 95-97

SW	Southwest
W	West

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1 INTRODUCTION

In modern eolian dune fields, dune-field patterns arise from the autogenic behavior of dunes (i.e., dune-dune interactions) and the external environmental boundary conditions within which the autogenic behaviors operate. Models of dune pattern formation reveal that if autogenic behaviors alone are considered a generic pattern emerges with little variability in the pattern (Werner, 1999). However, much spatial variability arises from the interplay of boundary conditions (Kocurek and Werner, 1997; Werner, 1999; Ewing and Kocurek, 2010b) The shape of a sediment source region is recognized to strongly impact spatial variations in a dune field pattern (Ewing and Kocurek, 2010b). Where a point or line source of sediment feeds a dune field, crest line spacing grows in the downwind direction and the number of defects (i.e., dune terminations) decreases (Ewing and Kocurek, 2010a).

The spatial distribution of eolian geomorphological dune elements from an upwind source area is now relatively well understood (Ewing and Kocurek, 2010a). In modern dune fields, dune pattern evolution occurs as crest line spacing increases and defect density decreases away from a sand source area (Ewing and Kocurek, 2010). This spatial evolution in the pattern is a result of dune-dune interactions, which are the recognized autogenic mechanism by which dune-field patterns evolve. Is this spatial increase in crest spacing and a decrease in defect density apparent in the eolian rock record? Recognizing the geomorphological spatial signature that a sediment source imparts on a dune-field pattern generates testable hypotheses to investigate the eolian rock record.

To study the spatial variability present in eolian sequences, the ancient fluvial-eolian Norphlet Formation was selected. This unit was deposited during the Oxfordian, Upper Jurassic (Mancini et al., 1985; Marzano et al., 1988) and occurs in the subsurface of the southeastern United States extending across Louisiana, Mississippi, Alabama, and western Florida, and beneath the modern day Gulf of Mexico (Honda and McBride, 1981; Mitchell-Tapping, 1982; Mancini et al., 1985). The Norphlet Formation overlies the Louann Salt and typically is overlain by the Smackover Formation and it is an oil and gas reservoir in several locations in onshore and offshore Alabama, Mississippi and Florida (Mancini et al, 1985; Marzano et al. 1988, Ginger et al. 1995). Recent oil plays discoveries in offshore Norphlet Formation (Rydberg in 2014, Vicksburg in 2013 and Appomattox in 2010 by Shell and Nexen) have generated interest in determining spatial variations in the eolian architectural elements of the unit.

Based on the recognized geomorphological transition from the Paleo-Appalachians upwind source in the northeast, we hypothesize that the architectural components of eolian stratigraphy also will vary spatially from a source region by a decrease in the total number of internal bounding surfaces, increase in eolian set thickness and change in the stratification types related to dune crest line organization. Recognizing the spatial configuration of bounding surfaces and eolian stratification types provides a means to identify source areas, characterize reservoir geometries and heterogeneities and reconstruct ancient paleoenvironments.

The goal of this project is to infer the stratigraphic configuration of a limited area of the Norphlet Formation fluvio-eolian system, based on the preserved eolian and fluvial facies and the vertical and lateral variations from three cores recovered at increasing distance from inferred upland source areas. From the facies and stratigraphic analyses performed (1) significant temporal depositional and climatic changes in the system occurred during Norphlet Formation deposition, from the base to the top of the unit these variations are evidenced by a change from wet interdune to dry dune deposits, a stage of mainly dry dune development and a late phase of retreat of the dune field and limited sediment availability related to rise in sea level. (2) Increase of preserved eolian set thickness and decrease in first order bounding surfaces away from the sediment source was confirmed in area of study. (3) Preserved grainflow thickness show a general positive correlation with distance from the sediment paleosource

2 GEOLOGIC BACKGROUND

2.1 Eolian dune-field patterns and spatial variability in modern deserts

Dune crest spacing and defect density (i.e., the number of defect pairs per unit of crest length) represent the basic geometrical properties of a pattern (Werner, 1999), and in modern dune fields such as White Sands in New Mexico and Rub' Alkhali in Saudi Arabia, the dune spacing increases and defect density decreases away from the upwind source area (Ewing and Kocurek, 2010a; Ewing and Kocurek, 2010b; Al-Masrahy and Mountney, 2013) (figure 1A and 1B).

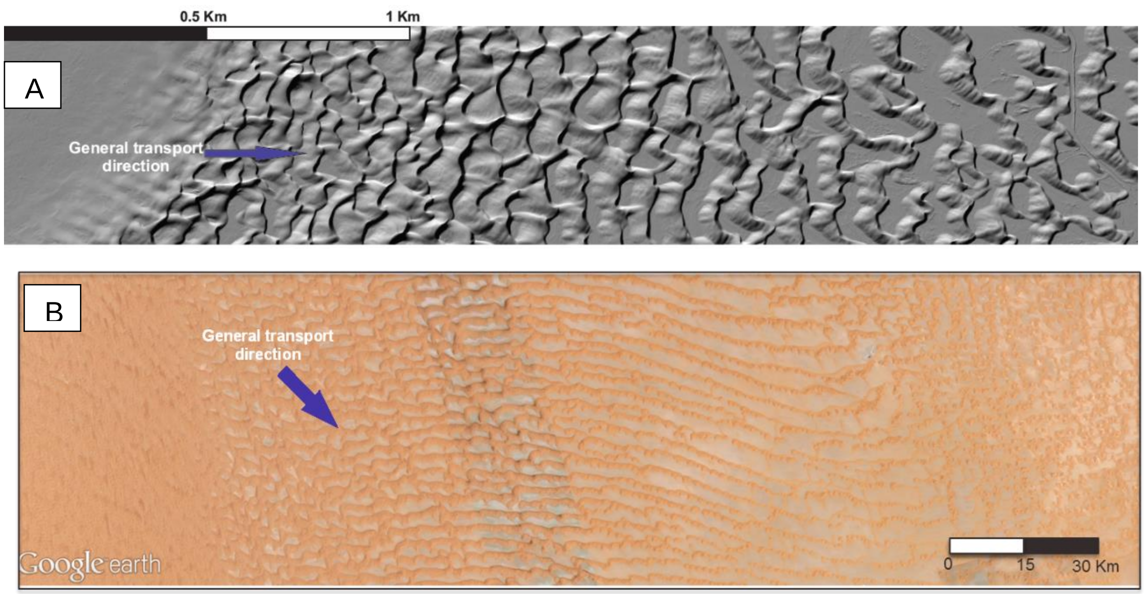


Figure 1. Dune pattern variability in modern dune fields. A) LiDAR image of White Sands, NM (Courtesy Ewing R.) showing dune pattern variability across the dune field. Higher defect density and lower dune spacing is observed in the upwind margin of the dune field (left side of the images) and more organized dunes with higher spacing between the crest is observed away from the source of sediment. B) Linear Dunes, Rub' Alkhali Desert, Saudi Arabia showing a similar behavior of White Sands but in a larger scale. Source: Google Earth.

In White Sands for instance, dunes formed at the upwind dune field margin are smaller, migrate faster and, due to their high defect density, are more susceptible to re-orientation by the secondary winter wind component, from NNW and SSE (Werner and Kocurek, 1997, Perderson et al., 2015). This situation results in a network-type pattern at the upwind margin, with more irregularly oriented and closely spaced crestlines (figure 1A). Whereas towards the center of the dune field, a more organized pattern, characterized by widely spaced crestlines with fewer defects occurs (Werner and Kocurek, 1997, Ewing and Kocurek, 2010b).

The configuration of sediment source and the dune field area geometry exerts an important control in dune pattern distribution. From a geomorphic stand point, dune fields can be classified by a point, line or plane geometry, based on sediment source area and dune field configuration (Ewing and Kocurek, 2010a). In the line source areas, the sand source originates along a linear geomorphic feature such as a beach or lake. The source area for White Sands, for example, is the deflation of an upwind playa lake (Ewing and Kocurek, 2010a).

In addition, dune spacing and crest length in a dune field evolve as a function of distance and time for point and line dune fields configurations (Ewing and Kocurek, 2010a). This means that areal changes in dune pattern are equivalent to the dynamic evolution of the dune field in time; for instance dune-field patterns initiate with the emergence of small dunes at the upwind sediment source and as dunes migrate away from the point or line source, bedform–bedform interactions (collisions and exchange of sediments between dunes) give rise to an increase in spacing and more organized dunes over both time and distance (Ewing and Kocurek, 2010a). As the dune field evolves into a more developed one, the effect of variations in certain boundary conditions (e.g. wind regime and sediment supply) over dune patterns become less important (Ewing and Kocurek, 2010b). For example in an early stage of a dune field, seasonal wind changes generate rapid dune re-adjustments in crestline orientations; conversely, when dunes reach larger sizes and more organized patterns, their re-constitution time is longer than the duration of the seasonal wind regime, therefore they tend to adopt a general bedform normal orientation (Ewing and Kocurek, 2010b). These pattern variability in time and space impart geomorphic heterogeneities in the dune field; and how dune-field pattern emergence within a set of boundary conditions is manifested in the eolian rock records is not yet well understood and the is the focus of this paper through the study of the main eolian architectural elements.

2.2 Eolian deposits in the rock record

In the rock record the main components of eolian deposits are sets of cross strata containing different stratification types and bounding surfaces (Kocurek, 1991). Cross strata is the product of the depositional processes of dune migration through time, which is measured with respect to the generalized depositional surface (Kocurek, 1991). In order for dunes to leave a deposit dunes need to move upwards or climb with respect to the depositional surface, resulting in a set of translatent strata. These surfaces created through bedform climb are time transgressive (Hunter, 1977a, and Rubin and Hunter, 1982). First order bounding surfaces (1st order BS) in eolian systems are formed by bedform migration and super surfaces are product of hiatuses in erg development (Kocurek, 1981; Kocurek, 1988). In addition to these major surfaces, reactivation surfaces or 3rd bounding surfaces are frequent in the eolian record and result of scouring or reorientation of the dune lee face during migration and represent stages in the advance of individual dunes (Brookfield, 1977, Kocurek, 1988 his figure 1).

Three main stratification types were recognized in the modern and ancient dunes deposits: grainflow or sand flow, grainfall and wind ripples deposition (Hunter, 1977a, Kocurek and Dott, 1981). Plane bed lamination could also occur but is rare, only forms when wind stress is too great for ripple formation (Hunter, 1977a). Grainflow strata are avalanche deposits produced by oversteepening of the dune lee slope. Grainflows form tabular bodies, in tapering upwards wedges that frequently truncate underlying foresets at low angles and approximates the angle of repose.

Grainfall laminae are produced by grains in saltation that lose momentum and settle down onto the dune slope. Grainfall displays indistinctly lamination and can occur from horizontal dip to near angle of repose. Wind ripple strata are product of tractional deposition and represent the migration and climbing of wind ripples under net deposition. These deposits are very thin laminated (i.e. millimeter scale) and inversely graded (Hunter 1977b, Kocurek and Dott, 1981)

Stratification types are used as an interpretation tool of the eolian cross-strata because they result from surface processes that operate on the dune, providing information about dune geometry related to wind direction. Also, the stratification type and its variability control the quality of eolian reservoirs because stratification type changes over short spatial scales and each type imparts a different porosity and permeability on a reservoir. In this study, the preserved stratigraphy from Norphlet Formation cores is studied in order to identify main changes in paleo geomorphology of the dune field as well as obtaining insight in the transport and climatic conditions of this ancient eolian system.

2.3 Norphlet Formation

The Norphlet Formation was deposited in the Gulf Coast basin during Late Jurassic (Oxfordian) time after the Louann Salt (Mancini, 1985). Initially it was recognized as a thin unit underlying the well-established reservoirs of the Cotton Valley Group and Smackover Formation in southern Arkansas and Northern Louisiana during the 1930's (Berg, 1986). The Norphlet Formation thickens and become a major sandstone towards southwest in Mississippi and Alabama, where later on was exploited as oil reservoirs (Harman, 1968; Badon, 1975; Mancini et al., 1984; Berg, 1986)

Typically, the Norphlet Formation directly overlies the Louann Salt, but in updip regions it unconformably overlies the Werner Anhydrite, Eagle Mills red beds, and other Paleozoic rocks (Tolson et al., 1983, Mancini et al., 1985). A stratigraphic column shows Norphlet strata age and stratigraphic bounding units in the onshore and state waters portions of the U.S. Gulf Coast (figure 2).

In southwestern and offshore Alabama, the contact between the Norphlet Formation and Smackover Formation can be gradational or abrupt (Mancini et al, 1985; Marzano et al. 1988). In parts of Mobile and Baldwin counties and in zones of Choctaw, Clarke, Escambia, and Washington Counties in Alabama the contact is conformable; whereas in most of Escambia County, the Norphlet Formation-Smackover Formation contact is sharp with carbonate mudstone overlying quartz-rich sandstone (Mancini et al., 1985). In other updip regions, the Smackover Formation carbonate rocks overlie Norphlet Formation conglomeratic sandstone (Mancini et al, 1985; Marzano et al. 1988).

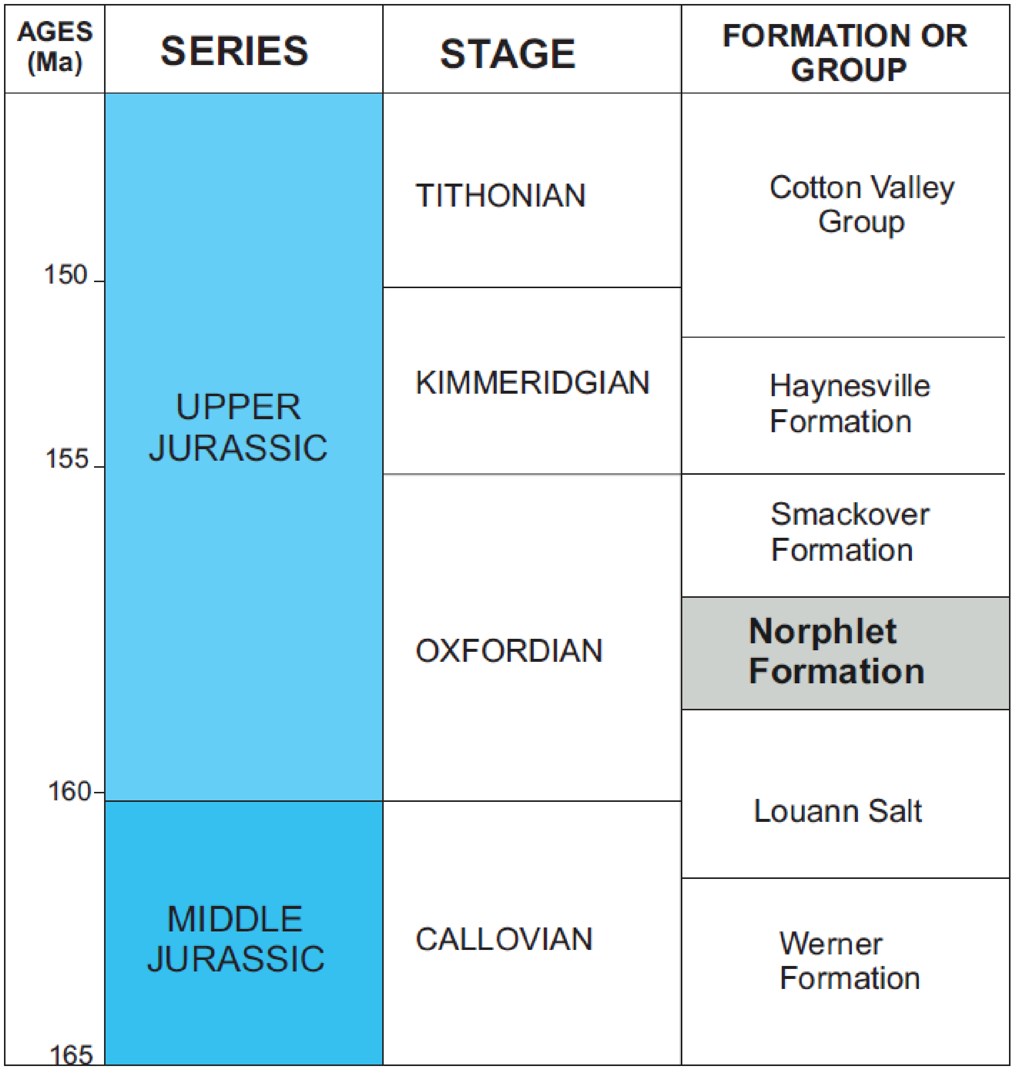


Figure 2. Simplified Jurassic stratigraphic column for the onshore and state waters portion of the U.S. Gulf Coast. The Jurassic Norphlet Formation is shaded (Modified from Mancini, 2008)

Towards Alabama, first descriptions of Norphlet Formation were a gray, clean sand, which was called the “Denkman Member” and initially considered as a Lower Smackover Formation facies by some authors (Murray, 1961; Oxley et al., 1967). However, it was recognized as a facies of the Upper Norphlet Formation (Hartman, 1968, Tyrrell, 1972; Pepper, 1982; Mancini et al., 1985; Marzano et al., 1988).

In zones relatively proximal to the source like Choctaw, Clarke, Monroe, and Escambia Counties in Alabama, the Norphlet Formation is characterized by red bed lithofacies composed of sandstone, siltstone, and shale (Mancini et al., 1985). These red beds grade to conglomeratic sandstone located in areas very close to paleo-highs (Wilkerson, 1981; Mancini et al. 1985; Welch, 2003; Ridgway, 2010). This lithofacies was interpreted as alluvial deposits, characterized by immature texture, lack of stratification and being partially matrix supported, suggesting debris flows as the primary transporting process (Mancini et al., 1985).

The optimal reservoir facies in the Norphlet Formation are the eolian sandstone that was deposited in a well-developed erg (Tew et al., 1991). That is the case in offshore Alabama, where Norphlet Formation can be up to 850 feet (260 m) thick (Tew et al., 1991; Ajdukiewicz, et al., 2010; Godo et al.,2011). Whereas in Panhandle, Florida the Norphlet Formation total thickness comprises up to 410 feet (125 m) (Douglas, 1991).

Regional facies maps for Norphlet Formation in Mississippi, Alabama and Florida based on cores and chips descriptions, well logs, 2D seismic, results of recent deep water wells and paleogeographic configuration during Norphlet Formation deposition proposed the following facies: wadi, eolian and basal shale (Hunt, 2013). In general Hunt's maps agrees with previous interpretations (Wilkerson,1981; Mancini et al.,1985 and Marzano; 1989), but also provide scenarios for the maximum extent of the Norphlet Formation eolian facies in offshore Alabama and Florida as well as the distribution of the water-born Norphlet Formation sediments. A potential down-dip limit of the eolian Norphlet Formation deposits in the Lloyd Ridge area (offshore EGOM) based on the results of the well LL-399, in which the Smackover Formation lies directly on top of the Louann Salt; probably associated with a transition from continental crust to oceanic crust (Hunt, 2013).

Diagenetic processes also play an important role in Norphlet Formation sandstone reservoir quality (Dixon et al., 1989; Taylor et al., 2004; Ajdukiewicz, et al., 2010) and are responsible for the presence of the “tight zone” in the Upper Norphlet Formation, produced by late stage high temperature quartz cement during deep burial. On the other hand, in the underlying good quality reservoir section, chlorite grain coatings prevented the pervasive quartz cement to reduce porosity (Dixon et al., 1989; Taylor et al., 2004; Ajdukiewicz, et al., 2010). The tight zone thickness varies in offshore Alabama from 10 to 190 ft. thick (3 to 58m) (Ajdukiewicz, et al, 2010) and in some onshore fields from 0 to 167 ft. thick (0 to 51 m) (Dixon, et al., 1989). This zone is recognizable in well logs as a drop in the resistivity curve and lower porosity readings (less than 8% log porosity and 1-md permeability) with the underlying Norphlet Formation strata (Marzano et al., 1988; Dixon et al., 1989; Taylor et al., 2004).

However diagenetic processes in Norphlet Formation varies from onshore to offshore, and impacting the formation petrophysical properties. For instance in some onshore Alabama fields, significant section of Norphlet Formation eolian facies have good preserved porosities but orders of magnitude lower permeability than the same facies in Mobile Bay (Dixon et al., 1989; Ginger et al., 1995). This is produced by the extensive development of pore lining and pore-bridging diagenetic illite in the onshore areas, a process that is not common in Mobile Bay (Ajdukiewicz, et al., 2010)

2.4 Tectonic and paleogeographic settings

The Gulf of Mexico (GOM) is a diverging margin basin dominated by extensional rift tectonics and wrench faults (Pilger, 1981; Miller, 1982; Salvador, 1987; Buffler, 1991). Three main phases are proposed in this basin: crustal extension and thinning, rifting and sea floor spreading followed by a phase of thermal subsidence (Nunn, 1984). During the active rifting stage (Late Triassic to Middle Jurassic) deposition was dominated by continental red beds and volcanic rocks deposited in rapidly subsiding grabens and the beginning of thick evaporitic deposits; whereas from Late Jurassic to Cretaceous the prevailing processes were crustal cooling and subsidence, corresponding to the shelfal position of marine carbonate, fluvial and deltaic siliciclastic rocks (Salvador, 1991).

The majority of the structural features that governed depositional pathways and thickness distribution of the stratigraphic units in the Northern GOM were formed during Middle Jurassic, as a result of crustal attenuation and transitional crust formation, which in turn created basement highs and lows and the accumulation of thick salt deposits (Sawyer et al., 1991). The main paleohighs during Norphlet Formation deposition in southwest Alabama were the Conecuh and Pensacola Ridges of the Appalachians, and less prominent the Wiggins Arch that extend westward into Mississippi (Mancini et al., 1985; Tew et al., 1991) (figure 3). Conversely, the most important depocenters in the area were Mississippi Interior Salt basin, Appachicola- Desoto Canyon Salt Basin in offshore Alabama, and farther east the Tampa Embayment (Mancini et al., 2001)

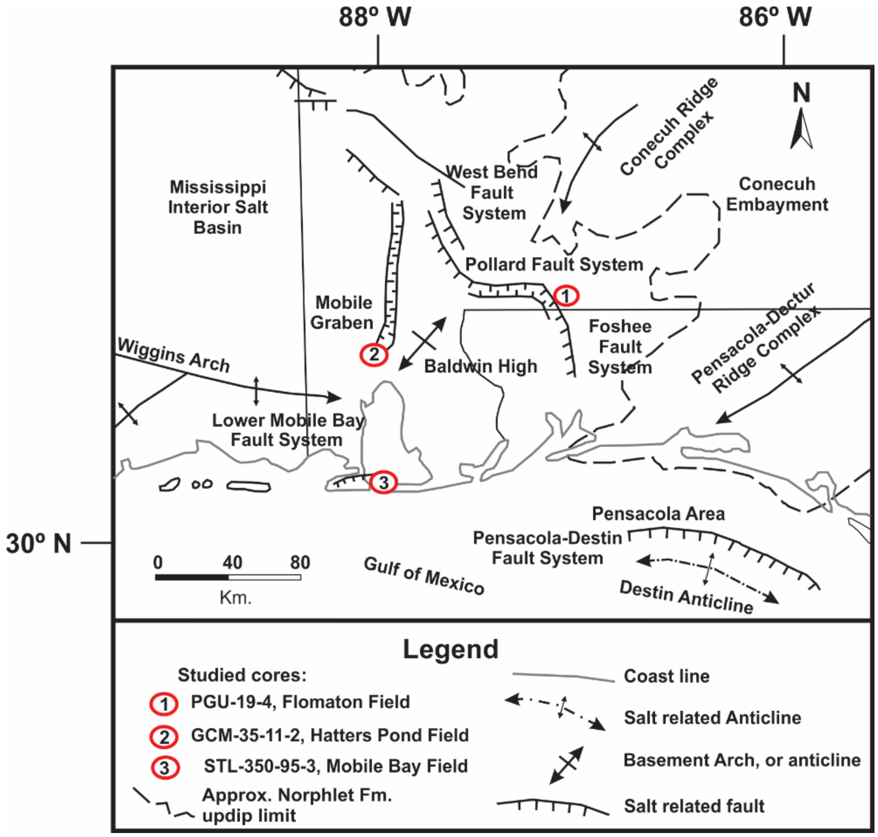


Figure 3. Map showing the main paleogeographic and structural features during Norphlet Formation deposition (arches and embayments) and cores location. PGU-19-4 in Flomaton field. GCM-35-11-2 in Hatters Pond field and SLT-350-95-3 in Mobile Bay area. Modified from Tew et al. (1991).

Norphlet Formation stratigraphic changes and thickness distribution combined with paleogeographic reconstructions suggest the Apalachian paleohighs represented the main source of Norphlet Formation deposits and also rimmed their north and east extent (Mancini et al., 1985; Marzano, et al., 1988). Minor positive features, such as Wiggins Arch could also have contributed sediments; as is evidenced by well penetrations on Wiggins Arch, where Norphlet Formation and Smackover deposits are missing (Cagle and Khan, 1983). The Appalachian Mountains restricted air and water circulation from the east during the Oxfordian, generating arid conditions in southwest Alabama, where the Norphlet Formation desert plain was developed.

More recently Lovell (2010) proposed an alternative provenance scenario for Late Jurassic Norphlet Formation sediments, particularly for east GOM areas (Destin Dome area). Based on U-Pb detrital zircon ages, the Pan-African Suwanee terrane (Gondwana affinity) is a potential source for offshore eastern Norphlet Formation deposits (Lovell, 2010). In addition to previously documented sources as the ancient Appalachian Mountains (Mancini et al., 1985, Marzano et al.) the Appalachian foreland basin, and Mesozoic rift basins were recognized by Lovell, (2010) as source terranes for Norphlet Formation sediments.

2.5 Study areas and local geology

The study area comprises southwestern Alabama in the Gulf Coast area of the United States, covering onshore to offshore locations. The oil and gas fields where the data occurs are: Flomaton Field, in Escambia County, Hatters Pond in northern part of Mobile County and Lower Mary Ann Field, offshore Alabama. Considering the paleogeographic settins during Norphlet Formation deposition, the selected cores are thought to represent a source-to-sink transect in the prevailing regional wind direction: northwest to southeast (Peterson, 1988), or approximately north to south (Hunt, 2013).

Salt movement has contributed to form most of the hydrocarbon traps in Alabama, generating salt-related structures (Mancini, 1985; Tew, 1991). Halokinesis in the study area began approximately by the Late Jurassic and many fault related structures cut the Louann Salt strata and terminate just above the Haynesville Formation, suggesting that the salt movement had diminished by the Early Cretaceous (Tew et al., 1991). Important structural features in Southwestern Alabama associated with salt movement include: The Pollard-Foshee fault system, the Mobil Graben and the lower Mobile Bay fault system (figure 3).

The Pollard-Foshee fault system is a group of extensional faults and grabens, in which the faults are oriented sub-parallel to the regional strike and roughly spproximates the updip limit of the thick Jurassic evaporitic formations (Tew et al., 1991). The Mobil Graben, is considered to be the eastern limit of the Mississippi Interior Salt basin (Tew et al., 1991). And the lower Mobile Bay fault system is an extensive set of Jurassic faults mostly oriented east- west, and interpreted as a pull-part graben system (Story, 1998).

2.5.1 Flomaton Field

This gas condensate field was discovered in 1968 (Mancini et al., 1984). The Flomaton field is located southward of the Conecuh Ridge complex and northeast of the Baldwin High and structurally consists of a low-relief faulted salt anticline associated with the Pollard-Foshee fault system, being the hydrocarbon trapping mechanism the nose anticline's fault truncation to the north (Mancini et al., 1984).

In this updip location Norphlet Formation facies were interpreted as mainly fluvial (wadis) and eolian facies (Mancini et al., 1985). Alluvial fans and wadis system might serve as transport pathways in Escambia County, shedding sediments southwards from the paleo Appalachian Mountains or from the wadis system from the east channeled within Mesozoic grabens (Hunt, 2013). A discontinuous basal shale facies was identified in cores from Flomaton field, described as black, structureless to wavy, illitic in composition and barren of fossils (Wilkerson, 1981; Mancini et al., 1985). These basal facies might correspond to intertidal deposits from Norphlet Formation or Louann Salt (Mancini et al., 1985).

2.5.2 Hatters Pond

Hatters Pond Field is situated in the south-central portion of the Alabama Interior Salt Basin and centered on the Stockton Ridge, a connection between the Wiggins Arch and Conecuh Ridge block (Higginbotham et al., 1990). The field consists of a north-south trending anticline that is approximately 13 km. long and 5 km. wide (7 by 3 miles) and it is limited to the east by fault that is part of the Mobile graben (Ginger et al., 1995). The hydrocarbon traps here involve salt movement along the west side of the Mobile fault system, that formed the faulted salt anticline (Higginbotham et al., 1990)

In Hatters Pond the Norphlet Formation was subdivided in three units: Red Beds, Lower Denkman with low- to high-angle cross-stratification and the more massive Upper Denkman occasional slightly horizontal, wavy and discontinuous laminae (Wilkerson,1981; Mancini; et al 1985). However, Lower and Upper Denkman are difficult to recognize in well logs whereas the red beds are differentiated by a serrate pattern of the SP log (Wilkerson, 1981; Higginbotham, 1990). At Hatters Pond the contact between the Norphlet Formation and overlying Smackover Formation is sharp, with thin stringers and scattered isolated Norphlet Formation clast in the basal section (1 m) of the Smackover Formation (Ginger, 1995).

2.5.3 Mobile Bay

The Mary Ann field is located approximately 56 km. southwest of the Pollard-Foshee fault system and is separated from the north and northeast Norphlet Formation onshore trend by tectonically stable areas like the Baldwin High and Wiggings Arch (Marzano et al., 1988). In this area the basement structural configuration allowed thick evaporitics deposit that with subsequent salt movement generated hydrocarbon traps (Marzano, 1988, Story, 1998). The fault complex creates a basinward deepening of the Norphlet Formation Formation, with depths ranging between 21000- 22000 ft. (6,400 to 6,700 m.); (Tew, 1991; Story, 1998).

This offshore location represent the “sink” of the study transect, in this area the Norphlet Formation was mapped as a complex of linear dunes oriented northwest-southeast, with thickness ranging from 400 to 600 ft. (120-180 m.) in the dune lenses (Story, 1998, Taylor, 2004, Ajdukiewicz, et al., 2010, Hunt, 2013). Mainly eolian sedimentation dominates this location during Norphlet Formation deposition: sand sheet, avalanche, wind ripple, grainfall, adhesion ripple, evaporitic and marine re-worked facies occur at the top (Marzano, 1988). Sabkha basal deposits composed of anhydrite sandstone occur at the Louann Salt- Norphlet Formation contact (Markham, 1991). The anhydrite forms massive mottled layers up to 13 cm. thick and with irregular shaped clasts up to 2.54 cm. diameter (Markham, 1991). Farther offshore Alabama, in the Desoto Canyon region, the Vicksburg well penetrated basal red-brown lacustrine mudrocks interbedded with silty/sandy laminae (Godo et al., 2011).

3 DATA AND METHODS

The studied data set consists of drill cores and well logs, the data were provided by the Alabama Oil and Gas Board, and a previous thesis. A transect from updip to downdip of the studied cores includes: Powell Gas Unit 19-41 (PGU-19-4) with a cored section of 23.5 m (77 feet), Getty Creola Minerals 35-11-2 (GCM-35-11-2) with 41 m. (135 feet) of core, and the offshore well State Lease 350 (track 95) #3 (STL-350-95-3) with a cored section of 172.2 m (565 ft.). The first two cores correspond to vertical wells, but the ST-350-95-3 is a deviated well with an inclination angle that ranges from 25° to 33° and azimuth from 89° to 97° in the Norphlet Formation section (table 1).

Well Name	Relative location to Paelosource	Type of Well	Norphlet Bottom Core Depth M.D. (feet)	Top Core depth M.D. (feet)	Apparent Thickness (feet)	Apparent Thickness (m)
Powell Gas Unit 19-41 (PGU-19-4)	Updip	Vertical	15502	15425	77	23.5
Getty Creola Minerals 35-11-2 (GCM-35-11-2)	Updip Intermediate	Vertical	18358	18223	135	41.1
State Lease 350 (track 95) #3 (STL 350-95-3)	Downdip	Deviated (aprox. 30 deviation)	22254	21689	565	172.2

Table 1. Core data and thickness used in this study.

In eolian deposits typically the lowermost section of migrating bedforms experience accumulation and preservation into the long-term stratigraphic record, whereas the upper part of the bedform (commonly the upper 90% or more of a bedform) are eroded by the advance of the following bedform in the train via ripple or dune climbing (Rubin and Hunter, 1982). Therefore, the proportion and distribution of the preserved eolian elements, do not necessarily depict the original proportion and distribution of these stratigraphic elements (Rubin and Hunter, 1982; Rubin and Carter, 2006).

Because eolian systems are formed by migrating bedforms, the resulting bounding surfaces are erosive in nature and their extent is controlled by the dimensions of the dunes and wind and other boundary conditions. Stratigraphic correlations based on well data are difficult, especially for features below seismic resolution. This situation occurs, due to the variability in architectural element geometries and orientation, in addition to the common absence of continuous bounding surface that represent reliable markers for correlation purposes (Mountney, 2006; Romain and Mountney, 2014). For instance, core data only provides a small section of the stratigraphic elements of the system, depending how the well penetrated the preserved deposits (Romain and Mountney, 2014). Thus, there is no way to directly determine extension of dune elements like grainflow width and length from core data, but one can measure vertical thickness of preserved grainflow (Kocurek and Dott, 1981; Howell and Mountney, 2011).

Consequently, the nature of the data set for this study can be considered as “one dimensional” as described by Romain and Mountney, (2014). To overcome the limitation of the continuity of the data, cores and well logs information need to be associated with analogue eolian outcrops that were deeply studied (e.g. Permian Cedar Mesa Sandstone of the Cutler Group and Jurassic Navajo sandstone in Utah). In these units, several authors measured preserved set thickness and grainflow parameters such as: length, width and thickness; in order to find three dimensional relationships among them (Kocurek, 1982; Mountney and Jagger, 2004; Romain and Mountney; 2014). Then, statistical measurements from eolian analogues can be compared to the Norphlet Formation core data.

Applying the methodology mentioned above, a first-order of magnitude prediction of the geometries and distribution of preserved dune and interdune elements of the Norphlet Formation can be obtained in the study transect and integrating that with the stratigraphic interpretation from cores, provides a way to understand the spatial variability of the eolian deposits.

3.1 Core description and stratigraphic columns

For the first stage of the project, detailed core descriptions were determined at the core house in Alabama Oil and Gas Board in Tuscaloosa and at Texas A&M sedimentology laboratory in College Station. Cores were described bed-by-bed to identify lithology, grain size, color, sedimentary structures (eolian and fluvial), bounding surfaces, lamina set and bedset configurations and dip angles. This information was the input to build each digital stratigraphic column.

Subsequently, set thickness was obtained from each core, based on the identification of bounding surfaces. The main parameters used to identify bounding surfaces and their hierarchy were the geometrical relationship between the underlying and overlying laminae, such as changes in dipping angles and truncated lamina (e.g downlaping and toplap terminations). In addition, other parameters such as variations in grain size, sorting and changes in the spacing of laminations and sedimentary structures within the bed were evaluated. In some cases these surfaces were very obvious and recorded by the core, but other times the change was more gradational but revealed by textural parameters. Depending on how sharp the contrast was and the cyclicity of the stratification type, each surface was classified as 1st order bounding surface or as a reactivation surface (3rd order BS), following the terminology of Kocurek, (1981) and Kocurek, (1988). Yet, some degree of uncertainty in differentiating between these two types of surfaces occurs due to the lack of lateral continuity in cores. In this study second order surfaces are not included.

For instance, 1st order BS in the cores represent erosional contacts frequently accompanied by an important change in laminae dipping angle and also mark a change in the stratification type from the underlying interval or a change from interdune to dune facies. On the other hand, reactivation surfaces were assigned to minor changes in the angle of the beds or minor erosional surfaces but the cyclicity of the stratification type and sedimentary structures of the overlying and underlying interval are similar.

Measurement of grainflow thickness within representative sets also was determined. This step was based on photographic record of described cores, using Image J software. A known scale was assigned to the picture and then the thickness of the grainflow was measured perpendicular to the dipping laminae. In cases that the grainflow showed changes in thickness across the core, the thickest section was measured (figure 4). Grainfall thickness was not measured because it is not generally observed. The vertical facies arrangement in each location was analyzed to determine horizontal facies relationships and determine dominant depositional processes either in relative time or across the study transect.

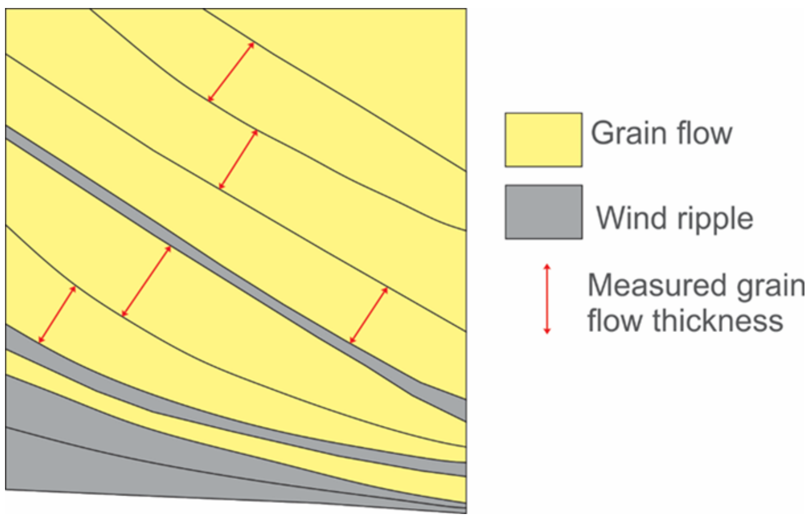


Figure 4. Diagram illustrating the measurement of grainflow thickness in cores. Red arrows indicate the way the thickness was measured in the pictures.

3.2 Dipmeter well data

Dipmeter logs from one of the cored wells and selected neighbor wells were interpreted to obtain dip direction trends and angles of preserved dune foreset and bottomset strata. Dipmeter data digitized by Hunt, (2013) were incorporated and dipmeter log from STL-350-95-3 was digitized using Neuralog software. In order to obtain similar quality data, only dipmeter logs younger than 1983 were included (which provide 10 - 20 measurement per foot, 0.3 m), because previous generations of this logging tool provided structural dip rather than stratigraphic bedding directions at a coarser resolution (1-2 measurement per foot).

Rose diagrams for each well were plotted and analyzed for each sector. The main purpose of this step is obtaining the azimuth direction of the bedforms cut by the well to determine main transport directions and its variability in space and in time across the study transect.

Dipmeter data is very useful especially for the deviated well ST 350-95-3, since the dipping angle readings from the log are already corrected by well deviation. Then, this data was used to obtain corrected dipping angles, which in core are apparent, generating “very steep” stratification (e.g. higher than the repose angle). However, it is important to consider that the resolution of this well log is coarser than measurements made in cores, so this measurement represent dipping strata trends.

4 RESULTS

4.1 Facies and facies associations

Four facies associations were interpreted for the Norphlet Formation and one additional facies association corresponding to the transition of the Norphlet - Smackover Formations was identified in the studied cores, a detailed facies description is included in table 2. Based on the vertical arrangement of the facies and their textural characteristics and sedimentary structures, the following facies were interpreted:

Interdune (EI) facies association consists of facies 1 and 2, only seen in well PGU-19-4 (figure 5). These deposits are mainly siltstone with interlaminated lenses of very fine sandstone with wavy and irregular laminations and sparse vertical burrows.

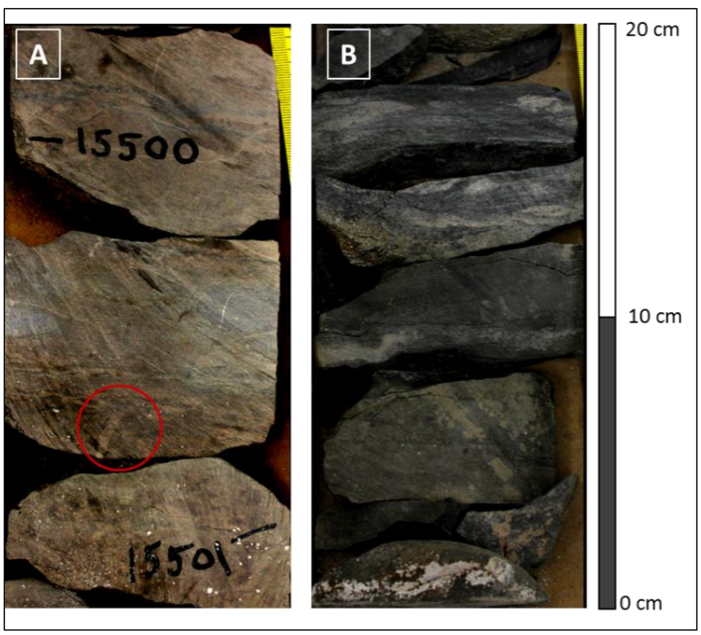


Figure 5. Interdune facies association (EI). A) Left picture corresponds to facies 1 comprised of very fine sandstone interlaminated thin siltstone laminae displaying irregular and wavy lamination and scarce vertical burrows (in red circle). B) Right picture corresponds to facies 2 of black siltstone with thin lenses of very fine sandstone. Both from core PGU-19-4, Flomaton Field.

Fluvial (wadis) and marginal eolian deposits (FE) facies association is comprised of facies 3, (figure 6). This facies is characterized by poorly sorted fine sandstone with a minor coarse sand and gravel fraction with abundant parallel lamination. This facies association occurs in PGU-19-4 core (15488 to 15479 ft. depth interbedded with ED facies association and from 15474 to 15488 ft. only FE deposits, see appendix 1).

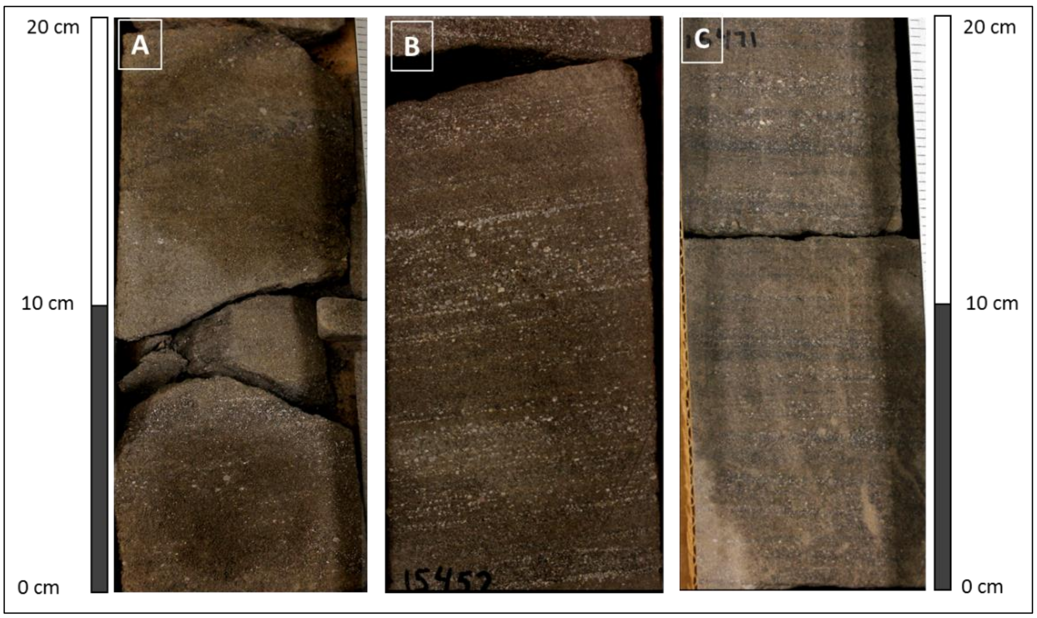


Figure 6. Fluvial (wadis) and marginal eolian deposits (FE) corresponding to facies 3. Note two main grain size populations and laminae vary from sub-horizontal to low angle. In B the coarse fraction appears normally graded along low angle lamination, laminae thickness in the millimeter range. Core PGU-19-4 in Flomaton Field.

Eolian dune (ED) facies association is composed of facies 5 (figure 7), characterized by moderately sorted to well sorted sandstone, rounded to sub-rounded, from very fine to upper medium grain size. This facies association represents preserved eolian elements such as grainflows, wind ripples, and grainfall, interbedding of these facies at variable inclination, from horizontal to high angle (25-30°) occurs. In addition, inclined beds without specific grading were identified, in this study these strata is called undetermined foreset strata. Abundant cross bedding and bounding surfaces occur throughout. These facies association is present in all the three cores.

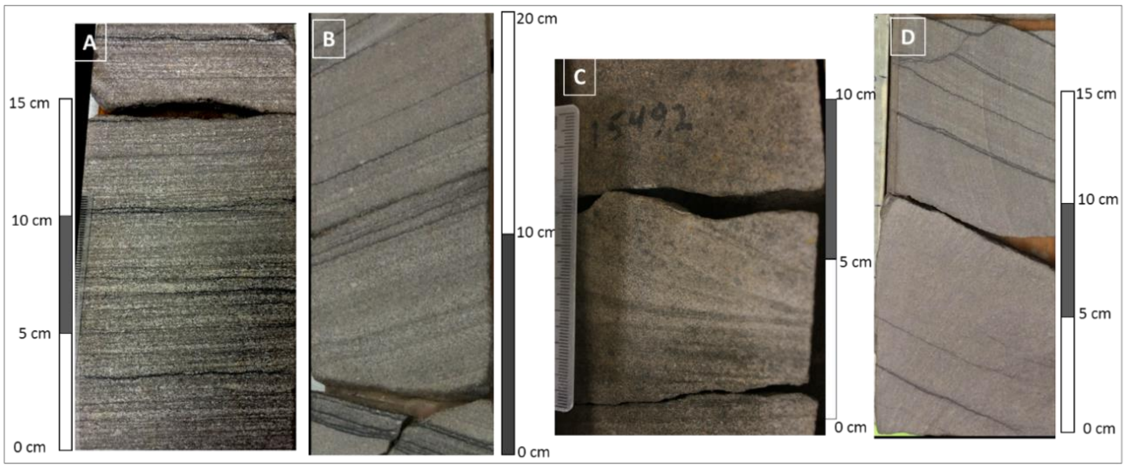


Figure 7. Eolian dune facies association (ED). A) Pin-stripe lamination typical of wind ripple strata (GCM-35-11-2 core). B) Grainflow strata with high angle beds, variable thickness and inverse grading, note the basal laminae displaying concave geometry and the cross bedding at the base (GCM-35-11-2 core). C) Grainflow toe, laminae thin and flatten laterally (PGU-19-4 core). 4-D: high angle parallel beds (undetermined foreset strata) interbedded with grainflow lamina to the top (GCM-35-11-2 core).

Sandsheets (ES) facies association is composed of facies 5, very fine to fine rounded sandstone. This facies displays horizontal to low angle parallel beds (< 15°) with typical faintly-defined laminae. Cross lamination is common and sparse thin grainflows with interbedded wind ripples occur. These deposits represent interfingering between sandsheets and poorly developed dunes and are recognized towards the upper section of Norphlet Formation in the three studied cores.

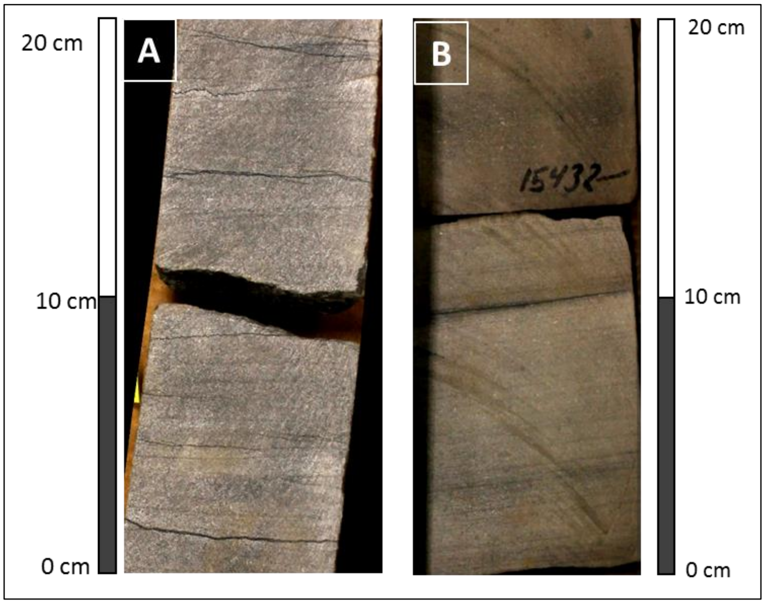


Figure 8. Sandsheets eolian facies association (ES). A) Shows discontinuous concave lamination and some cross lamination, stylolites are present (GCM-35-11-2 core). B) Corresponds to planar inclined lamination at low angle (PGU-19-4).

Marine facies association (M): consists of facies 6, very thinly laminated fine sandstone with interbedded dolomitic siltstone, displaying horizontal to very low angle lamination - bedding (<4°), sparse wavy lamination, and reworked sandstone (figure 9). It also includes facies 7, composed of structureless silty dolomite, which is recognized in GCM-35-11-2 core. This marine facies occurs in the three cores and is located in the uppermost section of the Norphlet Formation, below the Smackover Formation contact.

Facies Association Code	Facies Number	Lithology	Sedimentary Structures	Interpretation	Depositional environments
EI	1	Gray to light green very fine sandstone, interbedded with thin siltstone laminae 0.1-0.4 cm thick. This facies is only seen at the base of core PGU-19-4.	Irregular to wavy lamination lying sub-horizontal. Rare mud clast and sparse vertical burrows about 1 cm. high and 0.5 cm wide.	Wet Interdune	Eolian
	2	Black siltstone interbedded with lenses of beige very fine sandstone (0.2 to 0.5 cm. thick). This facies is only seen at the base of core PGU-19-4.	Subhorizontal lamination and sparse wavy lamination.	Wet Interdune	Eolian
FE	3	Gray to brown sandstone, dominantly fine with sparse 5-20% coarse grains (coarse sand to granule size) and poorly sorted. The fine fraction is subrounded, coarse grains are subrounded to subangular and appear normally graded along horizontal low-angle stratification. Abundant diagenetic black cement stains (pyrite, chlorite?). This facies is only recognized in core PGU-19-4.	Massive to low angle lamination (< 10°), abundant cross lamination. Rarely friable	Fluvial (wadis) deposits.	Fluvial-eolian margin
ED	4	Gray to light brown sandstone, fine to medium grained, moderately to well sorted. Grains vary from rounded to subrounded. Laminae thickness range from very thin (0.1 to 0.3 cm) to centimiter scale (1 to 10 cm). Some laminae show lateral thickness variation and inverse grading, rare concave laminae that taper and flatten laterally. In PGU-19-14 core this facies present black (pyrite,chlorite?) and orange cement stains (illite?). This facies occurs in the three cores.	Low and high angle lamination (up to 30°). Abundant cross bedding and paralell inclined bedding. Wind ripples, grain flow and scarce grainfall	Dune strata	Eolian Dune
ES	5	Light to dark gray very fine to fine sandstone, with rounded grains, moderately to well sorted. Bedding thickness centimeter scale (1.5 - 10 cm thick). Stylotites in GCM-35-11-2 core and frequent white cement stains (anhydrite, quartz). This facies occurs in the three cores.	Horizontal to high angle parallel beding (0-15°). Cross bedding, discontinuous laminae and concave lamimae. Sparse thin grainflows and wind ripples	Interbedded sandsheets with eolian beds	Sandsheets (erg margin)
M	6	Gray to black very fine sandstone well sorted with thin siltstone interbeds (0.3- 2 cm. thick). Rare beige cement stains (quartz, dolomite?). Abundant micro faults and stylolites. Facies encountered at the top of the three cores.	Horizontal to low angle laminae (<4°), abundant planar and and sparse wavy lamination. Scarce low angle cross bedding.	Marine deposits inter-fingered with reworked marginal eolian sands.	Marine- erg retreat
	7	Light gray silty dolomite, abundant white stains up to 2 cm diameter from diagenetic origin (anhydrite, dolomite nodules?). Only seen in core GCM-35-11-2	Massive	Marine transgressive deposits.	Marine. (Smackover Fm. basal interval)

Table 2. Facies and facies associations interpreted in the three cores for the Norphlet Formation and basal interval of the Smackover Formation.

Figure 9. Marine facies association (M). A) Represents facies 6 composed of black dolomitic siltstone with scarce sand laminations (core STL-350-95-3). B) Right picture corresponds to facies 7, light gray silty dolomite with light cement stains (core GCM-35-11-2).

4.2 Description of each location

4.2.1 Flomaton field, Powell Gas Unit 19-4 (PGU 19-4), depth: 15502-15425 feet

Vertical facies association

The Flomaton Field core is the most updip, source-proximal core studied and has large vertical variability of facies. The detailed stratigraphic column describing the 23.47 m. thick core is included in appendix 1. The following description is broken in the main sets or sections with similar facies association and separated by main bounding surfaces (1^{st} - and 2^{nd}- order BS).

The basal 2.4 m. are comprised of facies 1 and 2, which correspond to the interdune facies association. Key sedimentary structures and textural parameters to support this interpretation are the very fine grain size (very fine sand and siltstone), irregular and wavy lamination, and presence of bioturbation. These deposits are separated by a sharp contact (erosional) of the overlying section, composed of facies 4, with typical eolian dunes sedimentary structures like wind ripples, grainflow, grainfall and inclined dune strata (up to 15°). Cross bedding that generate change in the dipping direction of the lamination and bed occurs, defining two bounding surfaces within section. Therefore this interval of 2.93 meters (9.6 ft) thick, corresponds to the eolian dune facies association

An erosional contact (around 5.2 m. from the base of the core, 15,488 ft core depth) separates the previous eolian deposits from the overlying interval with alternating fluvial and eolian facies. Fluvial facies are characterized by coarse grained sandstone and conglomerate, which is interbedded with eolian beds of facies 4. This section is 3.14 m (10.3 ft.) thick and displays a fining upwards trend. Only two bounding surfaces revealed by the change of dipping angle and a sharp change in grain size occur within the interval. This assemblage of facies is interpreted as a fluvial, wadi deposits, with interbedded finer grain eolian dunes facies.

Around 8.3 m. from the base of the core (15,474 ft. depth) an erosive contact defines the next base of the interval, separating the very fine sandstone below from an overlying coarse and poorly sorted sandstone-conglomerate (facies 3), followed by thin beds of facies 4 (wind ripples and grainflow). The rest of the interval mainly consists of wadi facies. Low angle cross bedding is frequent in this section, defining individual beds of 10 to 65 cm, thick. This section is 5.12 m. thick (16.8 ft). The facies association for this interval are mainly wadis deposits with rare eolian dune facies.

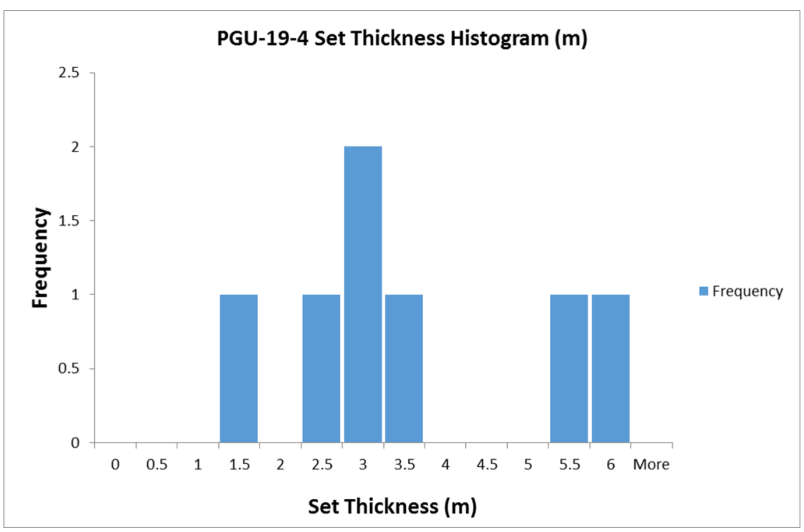
The next section starts 13.4 m from the base of the core (15,457 ft. depth) and is 2.83 m thick. This interval consists mainly of facies 5, showing sub-horizontal to low angle (< 5°) and subordinate facies 3 with cross bedding. The beds in this section are 24 to 10 cm thick and they become thinner upwards. This facies record wadis and sandsheets facies association.

The uppermost Norphlet Formation section in this core is located 16.3 m from the bottom and is 5.5 m thick (15488-15429 ft. core depth). This interval consists of facies 5, with very fine sandstone with sub-horizontal and low angle (< 5°) lamination and sparse coarse clasts, rare low angle cross bedding occurs. This correspond to the sandsheet facies association.

Finally a sharp planar contact defines the Norphlet -Smackover formation boundary at 22.5 m in the stratigraphic column that is equivalent to 15,430 feet depth in the core. This section consist of facies 13, with very thin laminated silty dolomite interbedded with very fine sandstone.

Set and grainflow thickness

Set thickness in this core varies from 1.5 (4.9 ft.) m to 5.52 m (18.1 ft.) with a higher frequency around 3 m, (Figure 10) however is important consider that in this location the bed sets are product of several processes: fluvial, eolian and marine. For instance, the thickest set (5.51 m.) corresponds to the upper section interpreted as sandsheet and marine deposits, whereas in the fluvial- eolian section set thickness ranges from 2.9 to 5 m thick. For this location the “sets” are not purely eolian, rather they are bed sets product of several depositional processes (figure 11).



PGU-19-4	
Mean	3.35
Standard Error	0.55
Median	2.93
Mode	#N/A
Standard Deviatio	1.45
Sample Variance	2.10
Kurtosis	-0.69
Skewness	0.63
Range	4.02
Minimum	1.49
Maximum	5.52
Sum	23.47
Count	7.00

Figure 10. Set thickness histogram for core PGU-19-14 and statistics sumary to the right.

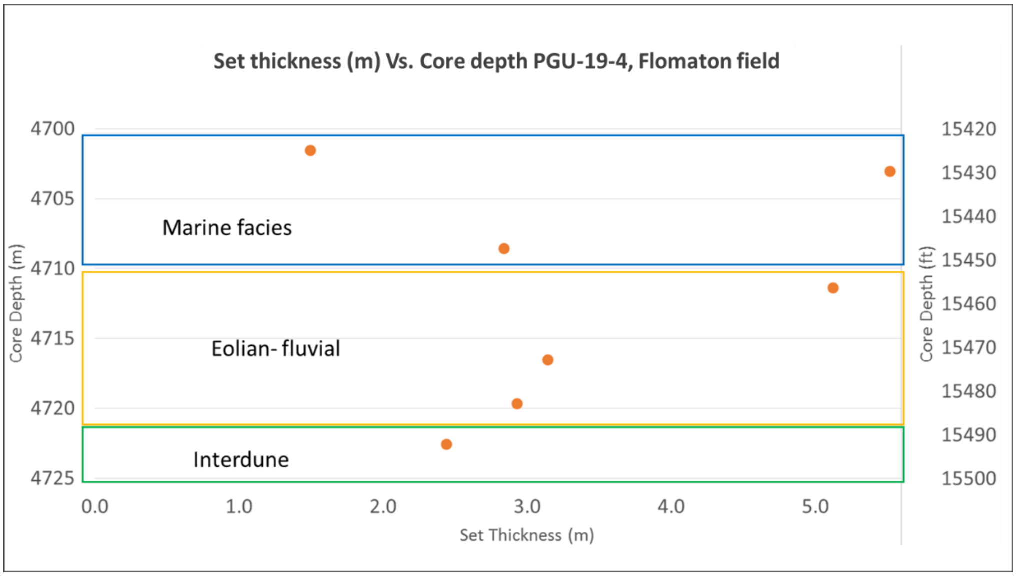
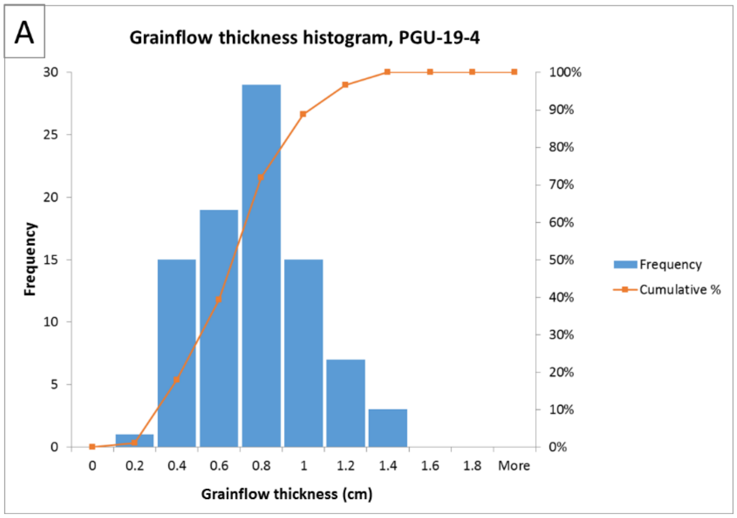


Figure 11. Vertical variability of set thickness (m) with depth, and facies associations, core PGU-19-4. Within the eolian section in this core, 89 grainflows were measured.

Their thickness ranges from 0.2 cm to 1.35 cm, with a mode of 0.66 cm and a fairly normal distribution (figure 12A). The thinner grainflows occur in low angle dipping sections (<6°), interbedded with wind ripple strata. The distribution of grainflow thickness and core depth is shown in figure 12B, where the lowest grainflows group and uppermost interval display a wider variety of thickness, whereas the intermediate depth has a narrower thickness distribution (0.5 to 0.9 cm thick)



PGU- 19-4	
Mean	0.66
Standard Error	0.03
Median	0.66
Mode	0.66
Standard Deviation	0.26
Sample Variance	0.07
Kurtosis	-0.26
Skewness	0.35
Range	1.16
Minimum	0.20
Maximum	1.35
Sum	58.99
Count	89

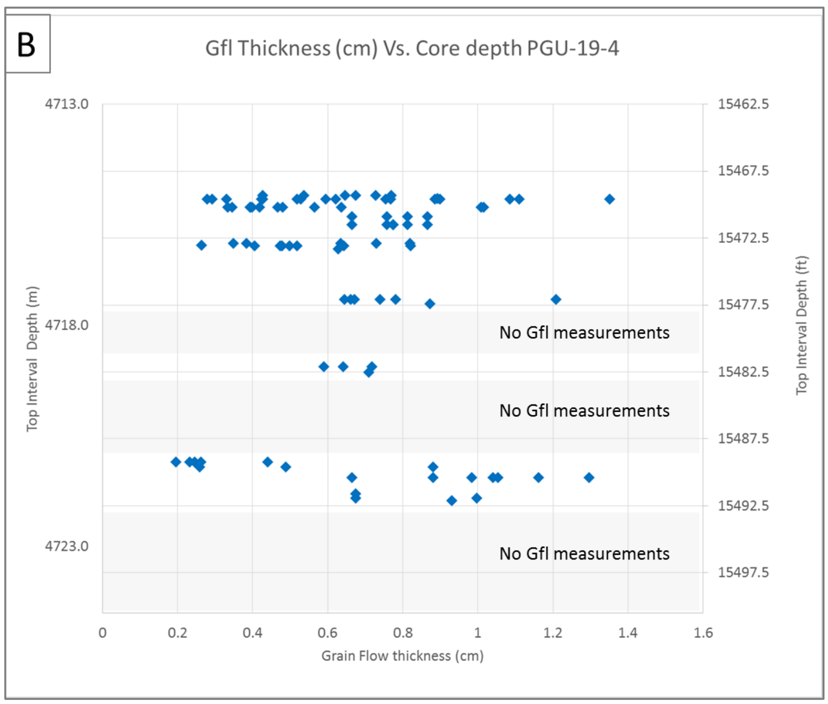


Figure 12. A) Grainflow thickness histogram for core PGU-19-14 and statistics summary to the right. B) Grainflow thickness (cm) versus core depth at the top of the interval where they were measured (shade area represents depth with no grainflows).

Interpretation for Flomaton Field core (PGU 19-4)

According to the vertical facies distribution observed by this core, temporal depositional variations occurred during Norphlet Formation deposition in this location. Varying from interdune deposits in the basal interval to eolian dune facies, that grades upwards to wadis and sandsheets facies. Finally is covered by the marine facies of the Smackover Formation. This alternating pattern of fluvial facies with eolian, indicates fluvial incursions in the updip eolian margin of the Norphlet Formation, that is known to laterally grade to alluvial facies in localities even closer to the paleohighs (Mancini et al., 1985). An important observation is that the core shows a general fining upwards trend and absence of eolian dunes and wadis facies in the uppermost section (sandsheets) that evidence the retreating dune field, and a wetter system, due to sea transgression which is clearly evident in the overlying carbonate rich siltstone of the Smackover formation. Based on the grainflow thickness, small dunes formed in this area, since most of them are thinner than 1 cm. thick. Also, in this core the highest dipping angle measured in the core was 15°, and the fact that only in three sets of eolian-fluvial strata occur also supports the idea of small dunes for this location.

4.2.2 Hatters Pond field, Getty Creola Mineral 35-11-2, (core depth 18358-18223 ft)

Vertical facies association

The studied core in this location corresponds to middle and upper Denkman Member of the Norphlet Formation, covering 41.15 meters (135 ft) of 68 m (224 ft) total Norphlet Formation thickness in this well. This core is mainly composed by facies associations of eolian dune (ED), sand sheets (ES) and marine deposits (M) towards the upper section. A detailed stratigraphic column is included in appendix 2.

The lowermost section (0 to 4.9 m) or 18358- 18342.7 feet depth is composed of facies 4 corresponding to sandstone from upper fine to medium grain size, with eolian sedimentary structures and low to high angle bedding (4-20°), this interval becomes finer upwards, but eolian sedimentary structures occur throughout. From 4.9 to 10.1 m (18342.7 to 18326.0 ft. core depth) two eolian sets are mainly composed by grainflow and wind ripple strata with a fining upwards trend. The upper section is dominated by sub-horizontal concave laminae and discontinuous lamina. Erosive basal contacts and cross bedding are very frequent defining abundant reactivation surfaces or 3rd order bounding surfaces and thin beds (most of them between 9-30 cm. thick).

A core gap interval of 6.09 m (20 ft.) is located between 10.1 to 16.2 m. (18.326 to 18306 ft. depth). From 16.2 to 23.6m (18306 ft. to 18281.5 ft.) very fine to fine sandstone of facies 4 with grainflows, wind ripples occur, displaying low to high angle laminations and common changes in dip direction. In general this interval displays a coarsening upwards trend. The core recovery in these section is not complete, generating uncertainty in the set thickness measurements.

The next section is 8.23m (27 ft) thick and is defined by a basal sharp contact around 23.6 m (18281.5 ft core depth) with an overlying concave upwards laminated sandstone with grainflows and wind ripple (ED facies association) but as one move upwards these structures are rare and it grades to undetermined foreset strata (also belonging to ED facies association) with very fine grain and frequent changes in dip direction and cross bedding. At 28 m (18267.15 ft core depth) a clear erosive contact with an abrupt change in grain size and geometry of the lamina defines a new eolian set. This section is composed of medium grain size sandstone with grainflow strata (facies 4) that steepens upwards (up to 30°) with clear erosional bounding surfaces evidenced by truncated strata terminations and frequent changes in dipping directions. The overlying set starts around 28.4 m (18265.73 ft) and is composed of a variety of eolian strata: wind ripples, grainflow and undetermined foreset. Towards the top of this set a coarser interval of wind ripple occurs mostly in sub-horizontal to low inclined beds (<10°) with rare high angle inclined beds (15°) and cross bedding.

From 31 m to 34.8 m in the stratigraphic column (core depth 18257.3 - 18244.65 ft.) two sets are composed of eolian facies 4, and 5 of undetermined foreset strata interbedded with sandsheets. Sub-horizontal and high angle bedding occur in this section and a fining upwards trend is recognized in this interval.

A 2.4 m. core gap occurs around 35.1 m (18243.85 ft.) and above it, lies the uppermost Norphlet Formation interval in this core, which is composed of facies 5 (ES), very fine to very fine sandstone with discontinuous lamina and low angle to horizontal lamination. Grainflow strata is rare but if present lamina is very thin and at low angle. In this section greenish diagenetic stains are common (chlorite?). Finally the sandstone is separated by the Smackover Formation silty dolomite (facies 14) by a sharp contact at 41.4 m (18,223.0 ft depth).

Set and grainflow thickness

Preserved set thickness (defined by 1st order bounding surfaces) in this location varies from 0.37 m (1.2 ft.) to 3.9 m (12.8 ft) with a mean of 1.96 m (6.4 ft.) and median of 2.28 m (7.45) (figure 13A). The vertical variability of the eolian set thickness shows a middle interval with interbedded thinner (<1.5 m) and thicker sets (>1.5), and these correspond to facies association ED located between 18306 to 18257.3 ft core depth (figure 13B) .The overlying sets correspond to sandsheet facies association and their thickness vary from 0.9 to 3.9 with a general thickening upwards trend. However, the spacing between reactivation surfaces is very close in this core, ranging from 0.06 m (0.19 ft) to 1.57 m (5.15 ft) generating thin beds within each eolian set.

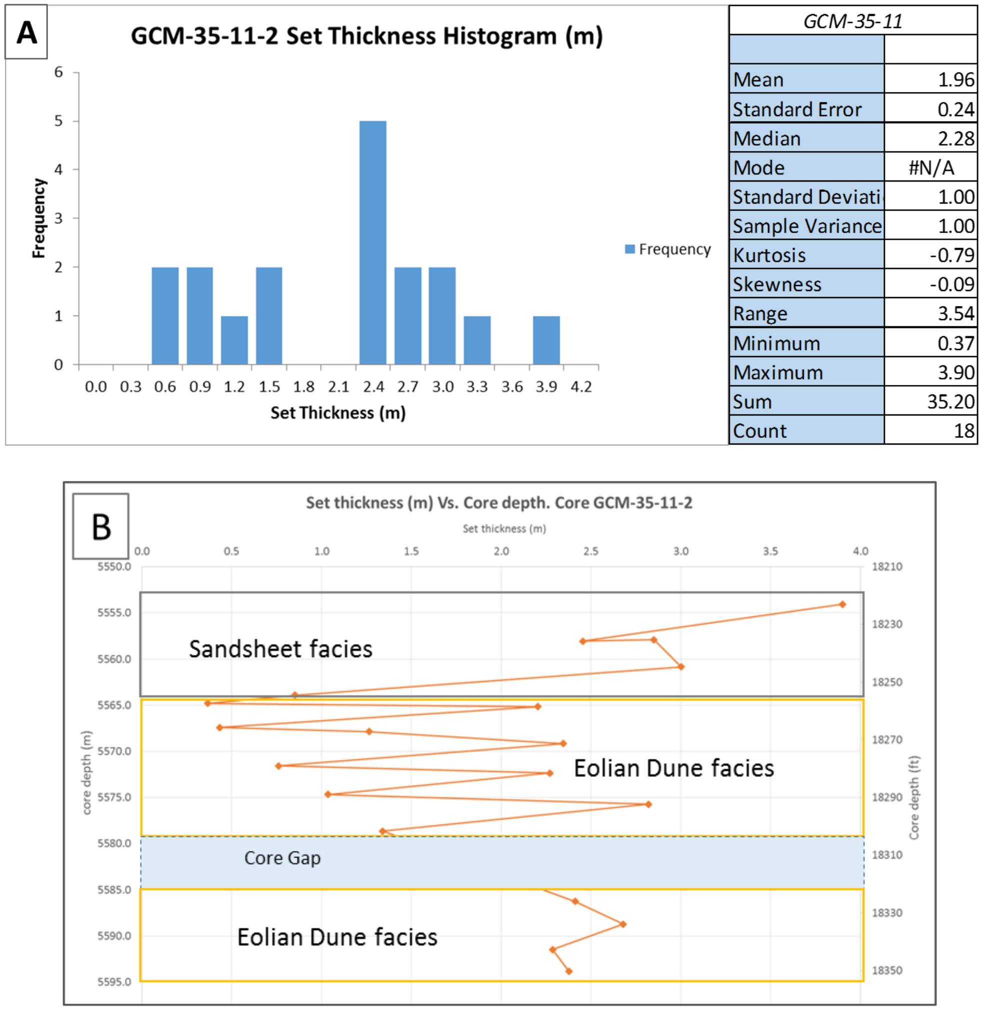
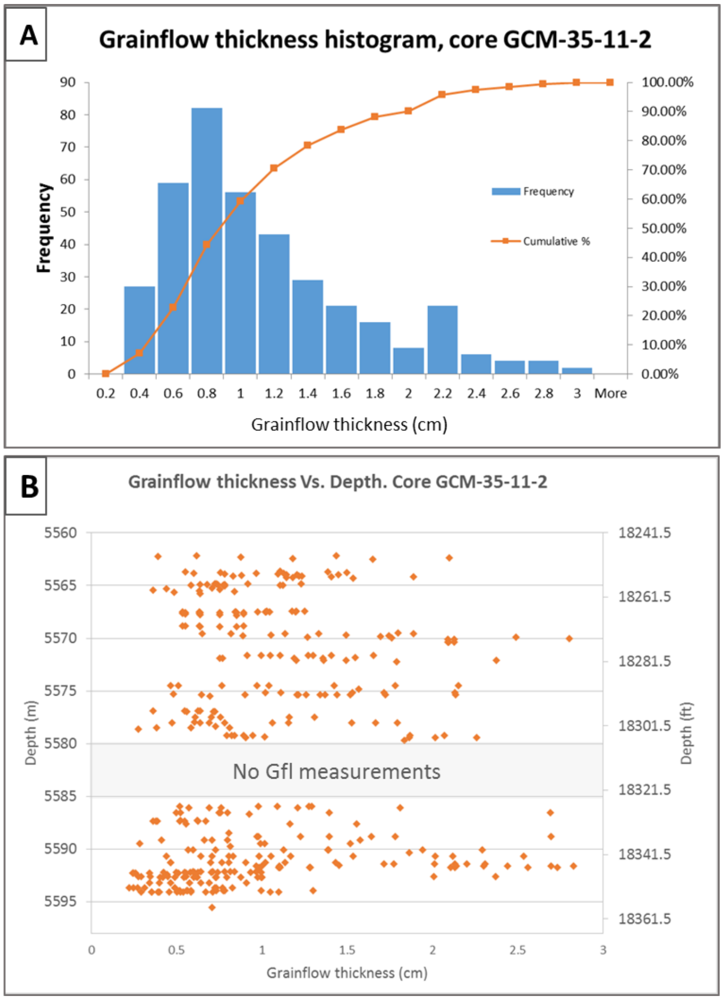


Figure 13. A) Set thickness histogram (meters) for GCM-35-11-2 core and statistical summary to the right side. B) Set thickness (m) versus core depth. Facies association indicated with colored rectangles, blue area represent missing core interval.

For this core 379 grainflows were measured, and their thickness varies from 0.22 to 2.83 cm with a mean of 1.03 cm (figure 14A). The distribution of these measurements, displays a left skewed distribution. The vertical distribution of grainflow thickness is scatter but the widest range of grainflows thickness are located between 5,588 and 5,592 m core depth (18,335 – 18,348 ft) (figure 14 B).



GCM-35-11-2	
Mean	1.03
Standard Error	0.03
Median	0.88
Mode	0.64
Standard Deviati	0.56
Sample Variance	0.32
Kurtosis	0.57
Skewness	1.07
Range	2.60
Minimum	0.22
Maximum	2.83
Sum	391.65
Count	379

Figure 14. Grainflow thickness (cm) for GCM-35-11-2 with statistic summary to the right. B) Grainflow thickness versus depth. Shade area represents the gap interval in this core.

Interpretation for Hatters Pond Field core (GCM-35-11-2)

In this location the analyzed Norphlet Formation core interval depicts only eolian facies association (ED and ES), interdune deposits were not recognized. However, there are some significant changes in grain size, nature of the bed contacts and sedimentary structures and texture from the bottom section to the upper interval that can be related to temporal changes in depositional environment.

A relevant character of this core is the abundance of change in dip direction and bounding surfaces throughout all the section, generating thin beds within the eolian sets (figure 15). These features are interpreted to result from variability in sediment supply that originated a very active area in the dune field.

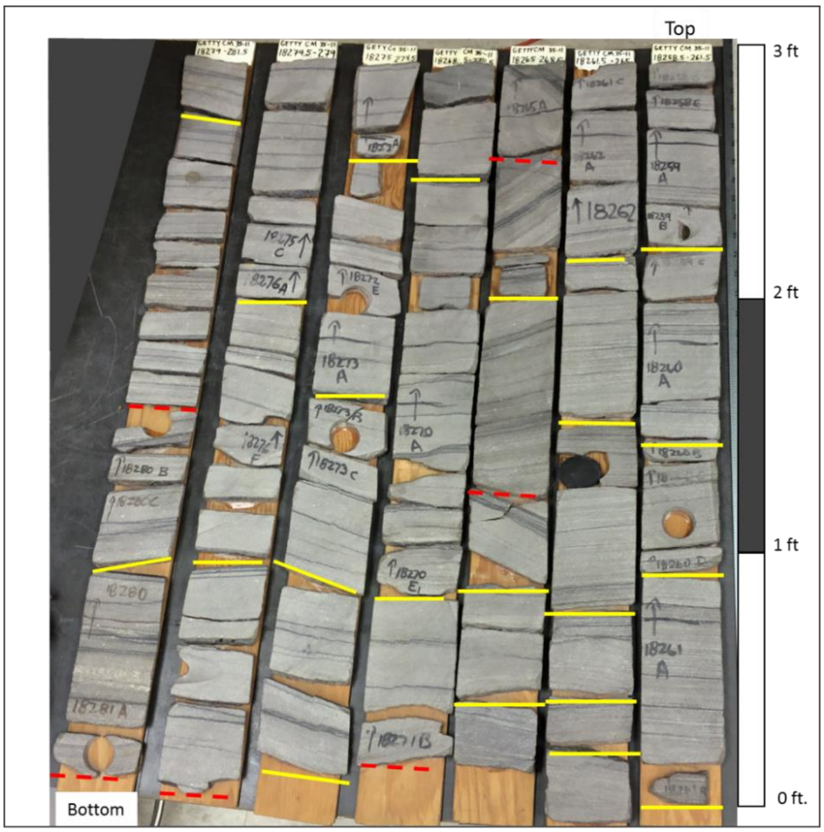


Figure 15. Core section of GCM-35-11-2 with main bounding surfaces defining eolian sets in red dotted lines (1^{st}. Order) and reactivation surfaces in yellow lines. Bottom left side is the lowermost section in this interval (18280.5 ft depth) and the top corresponds to the upper right corner (18,258 ft depth).

The core shows a general fining up trend, beginning at the base with medium to fine sandstone becoming fine to very fine sandstone. Another important change in the upper section from 32.8 m and up (18254 ft and up) is that eolian elements (grainflow, wind ripples and grainfall) are not predominant anymore, instead structureless inclined thick laminae or wavy lamination are common. This is interpreted to be sandsheets deposits and also coincides with the marine influence of the Smackover Formation transgression which is represented by its dolomite.

4.2.3 State Lease 350 (track 95) #3, Mobile Bay Field (core depth 22254-21689 ft)

Vertical facies association

The total Norphlet Formation thickness in this borehole is 172 m (565 ft), but the well is deviated (25° to 33° towards the east in the Norphlet Formation section) and the vertical thickness is approximately 150 m (495 ft). This core has a high recovery (95.2 %) with thin missing intervals. This Norphlet Formation core was divided in three main sections: lower, middle and upper based on the textural character of the rocks and their facies.

The lower section from 0 to 53.6 m (core depth 22253.9 to 22077 ft.) is dominated by fine to lower coarse sand grain with frequent bounding surfaces. Cross-bedding dominates this interval of core. Interbedded elements of facies 4 (grainflow, wind ripples, undetermined foreset strata) predominate. This assemblage corresponds to eolian dune (ED) facies association. Most apparent bed thicknesses ranges from 0.3 to 1 m. thick with a dipping angle (from dipmeter) between 1° to 29°

The middle section from 53.6 m to 109.2 m. (core depth: 22077 ft. to 21899.5 ft.) is characterized by fine to very fine sandstone with interbedded wind ripples and grainflows and undetermined foreset strata (facies 4 of ED). Beds (within eolian sets) show apparent thickness varying from 0.5 to 2.5 m with rare outliers. According to the dipmeter log the inclination of these beds range from 8° to 30°.

Finally, the uppermost Norphlet Formation section 109.2 to 164.5 m (21,892 to 21,790.7 ft core depth) consists of very fine sandstone and siltstones (facies 5,6 and 7) showing a fining upwards trend. These facies correspond to the facies associations of sand sheets interbedded with eolian dune facies and marine deposits in the uppermost interval. The angle of these beds cannot be interpreted from the core but dipmeter well log indicates horizontal to high angle with a flattening upwards trend (see next section). Within this upper section, an important 1st order BS was interpreted at 143.5 m (21,793.4 ft core depth) where a sharp change occurs from the underlying fine sandstone to a dark gray siltstone with carbonate content, wavy lamination and thin sand lenses. This contact also corresponds to subhorizontal bedding around this depth and low angle beds above it. This section is covered by the dolomitic siltstone (facies 6) of the Smackover Formation (21,709- 21,689 ft core depth), however the contact from the Norphlet Formation to the Smackover seems transitional in this core and the core did not cut enough thickness of the Smackover Formation to properly evaluate the nature of the contact.

Set and grainflow thickness

First-order bounding surfaces in STL-350-95-3 define sets as ranging from 0.21 m to 9.3 m thick (figure 16A). The most frequent values are between 1.5 and 4.5 m. in the histogram. The variability of set thickness in vertical (core depth) varies with alternating intervals of thin and thick sets, for the lower and middle section (composed by ED facies) and frequent sets thinner than 4 m, although they are overlain by thicker sets (figure 16 B). In the upper section of the Norphlet, which correspond to sandsheets, thick eolian sets predominate (> 4m).

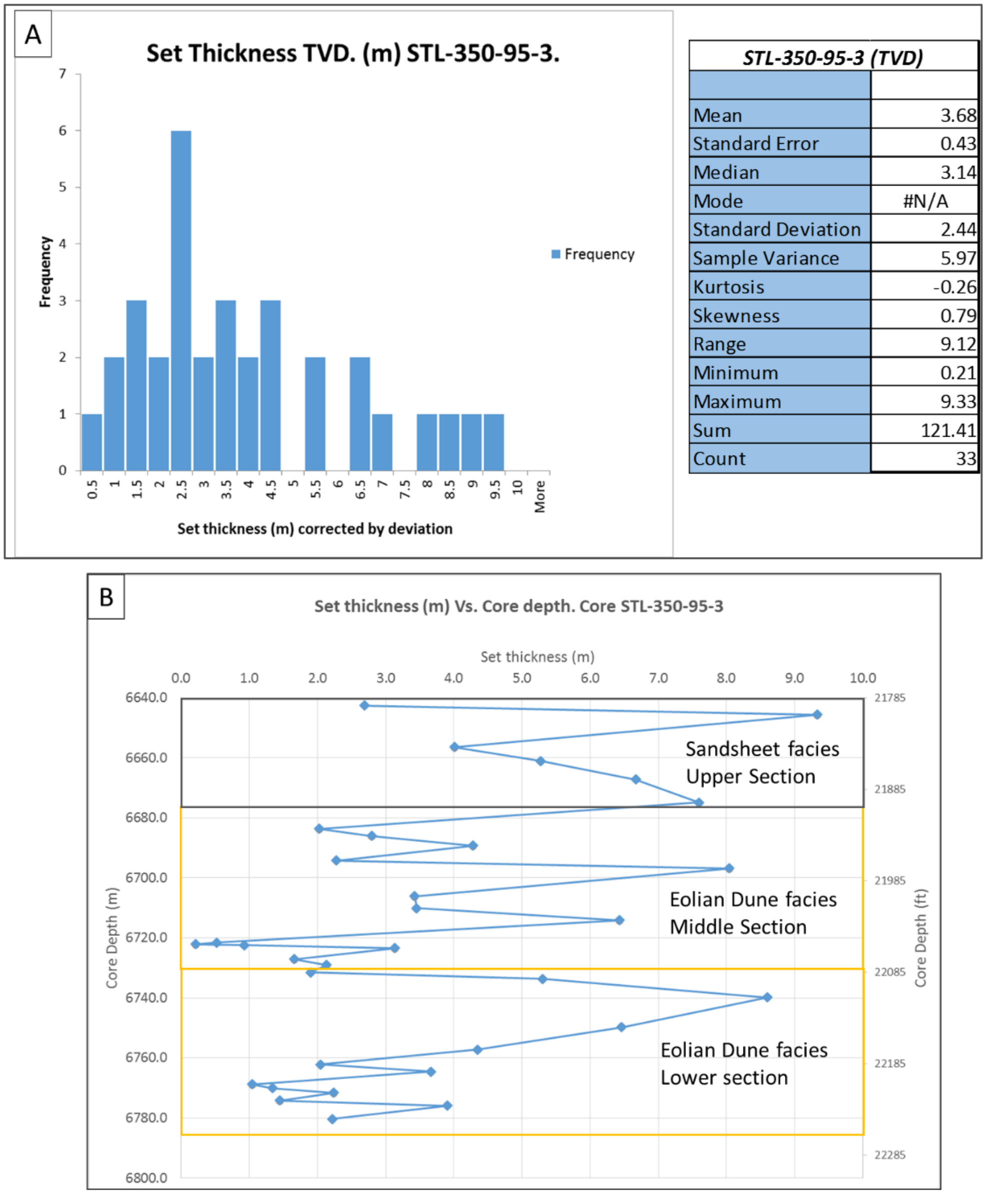
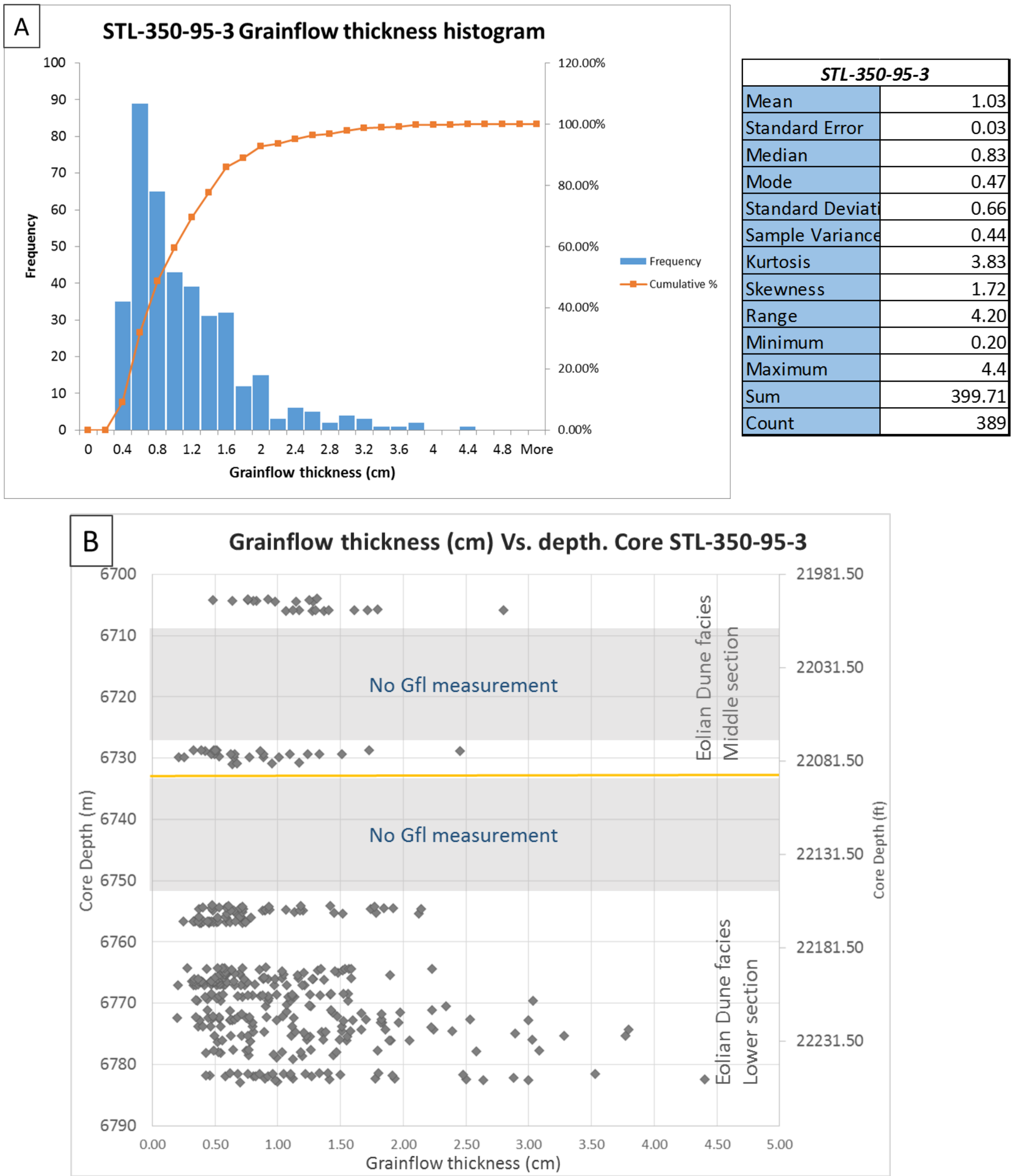


Figure 16. A) Set thickness in meters (corrected by deviation.) histogram for well STL-350-95-3. B) Set thickness in meters versus core depth in meters (left y axis) and feet (right y axis). Rectangles indicate main facies association.

In this core grainflow thickness varies from 0.2 to 4.4 cm with a mean of 1.03 cm (figure 17A). The histogram shows that the distribution is skewed towards the thinner beds, being 0.5 cm the mode. These values are higher than the measurements in the other two locations. The variability of grainflow thickness in depth is shown in figure 17B.



STL-350-95-3	
Mean	1.03
Standard Error	0.03
Median	0.83
Mode	0.47
Standard Deviati	0.66
Sample Variance	0.44
Kurtosis	3.83
Skewness	1.72
Range	4.20
Minimum	0.20
Maximum	4.4
Sum	399.71
Count	389

Figure 17. A) Grainflow thickness (cm) histogram STL-350-95-3, right side grainflow thickness statistic summary. B) Grainflow thickness (cm) versus depth for core STL-350-95-3. Shaded areas represent intervals with no measurements, either because grainflow were rare or nor present. Yellow line divide the lower and middle Norphlet Formation section. Note the thicker grainflows are present in the lower Norphlet section and they are very frequent, whereas in the middle section and upper (not shown) wind ripples dominate.

Interpretation for Mobile Bay (STL-350-95-3)

This location has the thickest eolian section and no interdune facies were recognized in the lower and middle intervals. The middle section, might reflect a period of less sediment availability or some spatial variability in the dune filed, generating less preserved eolian sedimentary structures than the lower section.

Set thickness suggest that this location might represent a more stable area of the Norphlet Formation dune field, with thicker dunes. However, the lower section of this core shows abundant changes in dipping foreset strata and clear bounding surfaces, and thin beds (up to 2 m). Whereas in the middle and upper section these bounding surfaces are widely spaced or with gradational changes between sets. This can be associated to variability in depositional system (e.g. dune dynamics) through time. For instance, the lower section might represent a stage of growth in the dune field but the middle can be associated with a more stable dune field with less changes in the orientation of the depositional bodies.

The 1st Order BS interpreted in the upper part of the core (at 143.5 m from the base of the core or 21,793.4 ft. core depth) represents the marine influence and the rise of sea level; indicating this was near the margin of the waning dune field. Although some remnant eolian sedimentary structures are recognized, the fine grains and the carbonate content represent the transition to the Smackover Formation carbonate.

4.3 Dipmeter data

4.3.1 Flomaton field

Rose diagrams from dipmeter well log data were plotted in order to evaluate bedding orientation: foreset strata direction in eolian deposits, and analyze vertical and lateral variability among wells. Figure 18 shows two rose diagrams corresponding to wells near the cored well

PGU-19-4 in Flomaton Field. These diagrams display scattered bed dipping direction, ranging from NW to S, the color scale indicates depth intervals.

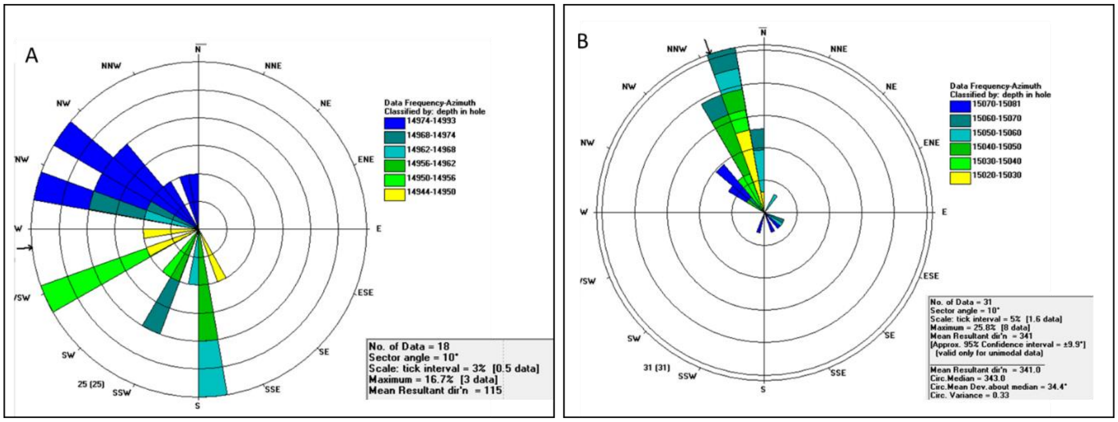


Figure 18. A) Rose diagrams from well Jone Trust 21-7-1 located 3.84 km east of PGU-19-4. (B) Rose diagrams from well A.T.I.C.-Northrup 31-1-1 at 10.5 km NW of PGU-19-4. Frequency of azimuth direction of foreset strata is represented by each sector (10° each) and the colors represent depth ranges with yellow being the shallowest and dark blue being the deepest. The dip intervals vary from NW to SE in both wells, and in A the shallowest beds dip toward the SW whereas the deepest dip to the NW. Reproduced with permission from Gutierrez and Ewing, 2015. Copyright (2015) by GCAGS Transactions.

It is important to consider the different depositional processes that occurred in this area, when analyzing the direction of the strata, because the interaction of fluvial and eolian processes might explain the variability in the bed directions. Thus, bedding direction in this area might not be the best proxy to interpret deposition direction of the dunes in this area.

4.3.2 Hatters Pond

In Hatters Pond field, the cored well (GCM-35-11) does not have a dipmeter log. Therefore a nearby well (HP-16-9-1) was analyzed. Foreset dipping directions are mainly in the SW quadrant and vertical changes are subtle, a slight shifting towards the west occurs in the upper section (Figure 19). This distribution has a clear preferential bedding orientation, which in this location corresponds to dune strata.

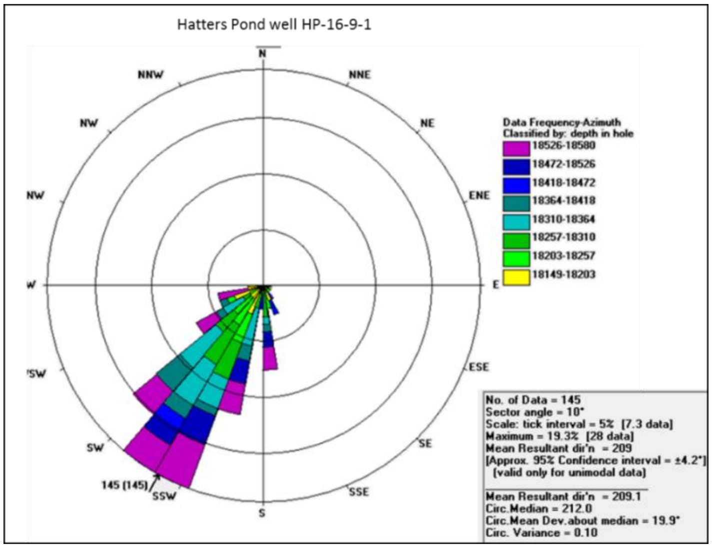


Figure 19. Rose diagram from dipmeter of Hatters Pond well HP-16-9-1, neighbor of GCM-35-11-2. Azimuth direction of foreset strata is represented in each sector and colors indicated depth range with yellow being the shallowest and purple the deepest. The dip directions are mainly to the SW and vertical changes are subtle. Reproduced with permission from Gutierrez and Ewing, 2015. Copyright (2015) by GCAGS Transactions.

4.3.3 Mobile Bay

Two rose diagrams from Mobile Bay area were plotted (figure 20). The cored well STL-350-95-3 is shown figure 20-A the other diagram correspond to well STL-9597, located 1.35 km. southwest from the cored well. In both wells the general strata dip direction ranges from NE to SE. In the STL 350-95-3 well younger strata dip towards the E-NE.

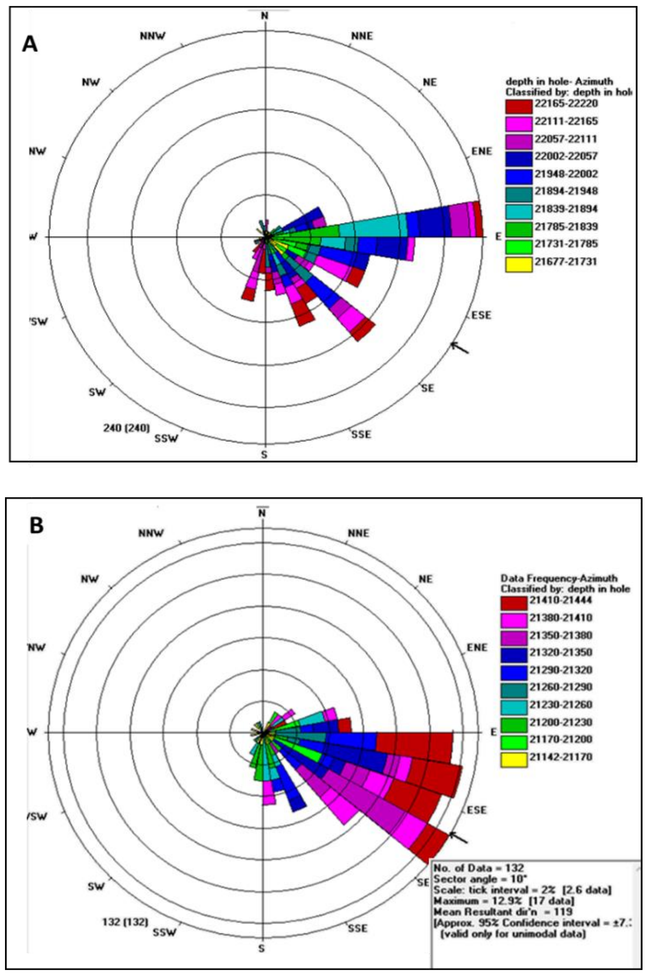


Figure 20. Rose diagrams from dipmeter logs in Mobile Bay. A) well STL 350-90-3, B) well located 1.35 km southwest of STL 350-95-3. Azimuth direction of foreset strata represented in each sector and colors represent depth ranges with yellow being shallowest and red deepest. Notice that dipping directions are mainly in ENE to S area and there is a change to NE directions in the shallowest part of STL 350-95-3. Reproduced with permission from Gutierrez and Ewing, 2015. Copyright (2015) by GCAGS Transactions

The dipmeter well log format provides another way to evaluate vertical variability and changes in dipping angle and azimuth in the cored well STL-350-95-3, in this case this well log helped obtaining more reliable bedding dipping angles corrected by well deviation. Figure 21 shows a section from 22,220 ft to 21,975 ft dipmeter log for this well (9.5 to 85 m in the stratigraphic column in appendix 3).

The first track shows the well log depth in feet, the second track displays tadpoles in blue with the circles indicating the inclination angle and the tails oriented according azimuth provided by the logging tool. The third track shows the azimuth value in a linear scale, finally a label with the interpreted Norphlet Formation division was included. Overlying the well log there are red dotted lines, corresponding to the 1st Order BS bounding surfaces interpreted in the core analysis.

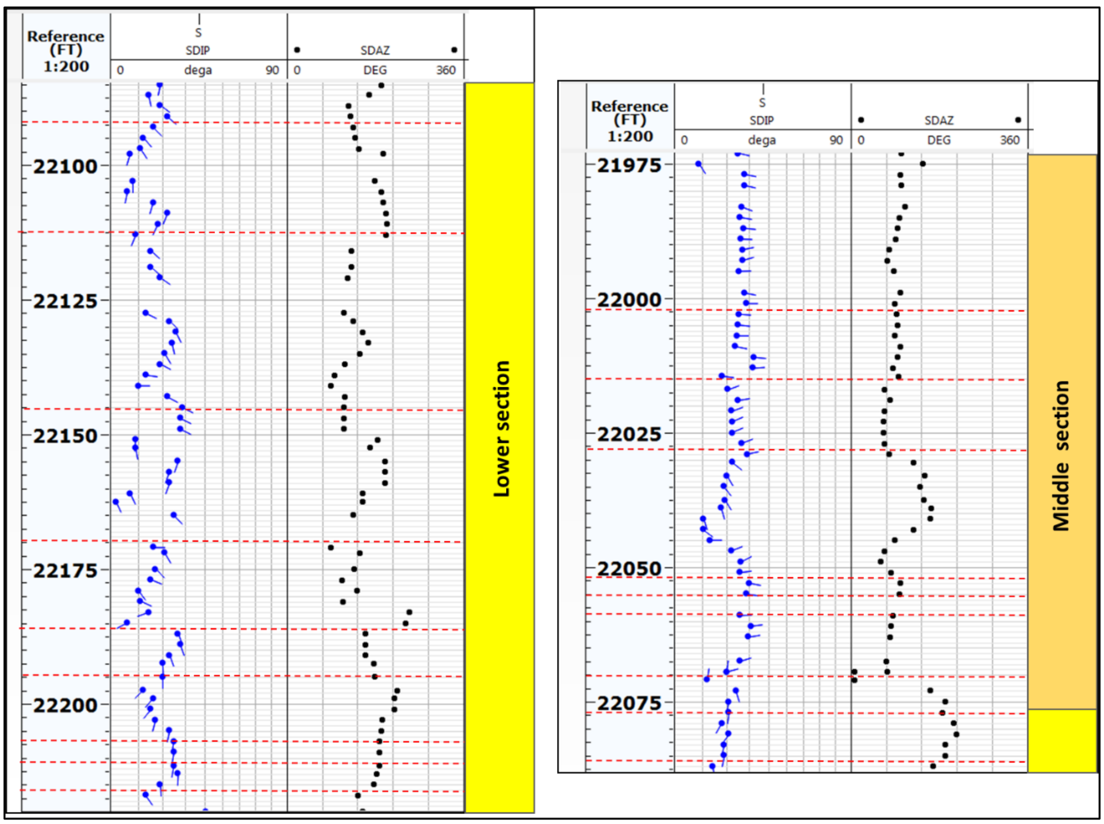


Figure 21. Dipmeter well log section from well STL-350-95-3 in Mobile Bay area, depth from 22,220 ft to 21,975 ft. Red lines correspond to interpreted 1st Order Bounding Surfaces identified in core. Blue tadpoles represent the bedding dipping angle (circle) and the azimuth of the bed (tail). Right column indicates the Norphlet Formation subdivision interpreted in core.

Most of the breaks in the tadpoles distribution coincide with a bounding surface; either displayed by a sharp change in dipping angle or in azimuth. However there are some breaks in the dipmeter that were not identified as 1st order BS in the core (e.g. depth 22160 ft. or 28.6 m in from the base of the core). This can be a limitation of the recognition of these surfaces in core (virtually no lateral continuity).

When an important drop in dipping angle occurs, it generally corresponds to a significant change in facies (figure 21). For instance, around 22,185 ft (21 m in appendix 3) depth a change in dipping angle from 28° in the lower bed to 6° in the overlying bed, coincides with an important facies variation: from thin laminated and fine grain sandstone of wind ripples strata in the layer below the surface to a medium to upper fine sandstone, fragmented and containing grainflows and interbedded wind ripple laminae (both facies belonging to ED association but different stratification types) (appendix 3). A similar situation was recognized in the interval from 22,141 ft. (34.4 m) to 22,128 ft (38.4 m) depth where there is a change from wind ripple strata to interbedded grainflow and wind ripple above the bounding surface.

In this display can be recognized the spacing of the 1st order BS varies in each unit of the Norphlet Formation (figures 21 and 22). In the upper section in this core, larger spacing between bounding surfaces occurs (figure 22). Moreover, the distribution of the tadpoles from 21,850 ft. to 21,800 ft (123 to 138 m) is very homogeneous with minor variations until it contacts the 1St Order bounding surface around 21794 ft.(139.5 m) depth, corresponding to an important change in facies.

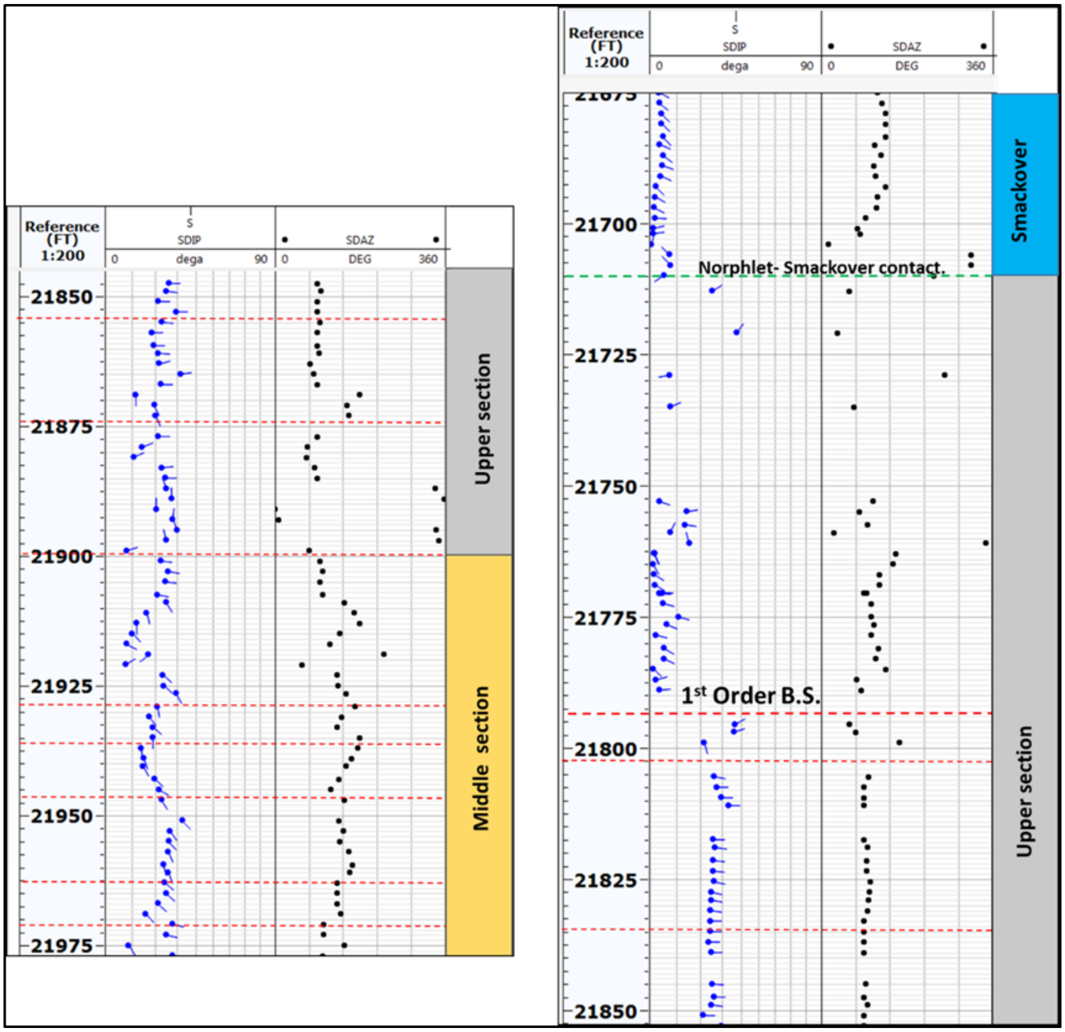


Figure 22. Dipmeter well log section from well STL-350-95-3 in Mobile Bay area, depth 219975- 21675 ft. M.D. Red lines correspond to interpreted 1st Order Bounding Surfaces identified in core. Blue tadpoles represent the bedding dipping angle (circle) and the azimuth of the bed (tail). Right column indicates the Norphlet Formation subdivisions interpreted in core.

In this well the majority of the bedding dips between 20° to 30° as can be seen in the histogram of the dipmeter well log (figure 23), however, 32% of the readings show dip angles between 5-15°.

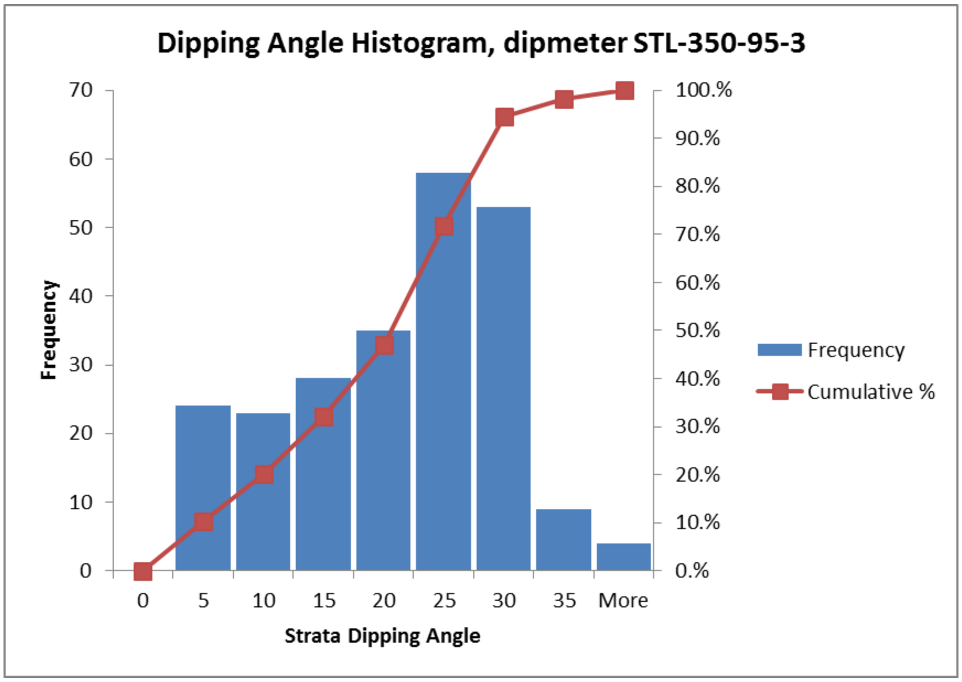


Figure 23. Histogram of dipping angles for well STL-350-95-3, from dipmeter well log.

5 DISCUSSION

5.1 Comparison among three locations: stratigraphic architectural elements

Preserved grainflow thickness show a positive correlation as the distance from the sediment paleosource increases. A histogram of grainflow thicknesses compares the studied three locations (figure 24). PGU-19-14, which is the closest to the inferred sediment input, has the thinnest grainflow; whereas GCM-35-11 and STL-350-95-3 show thicker grainflows with a large population ranging between 0.5 and 1.6 cm thick.

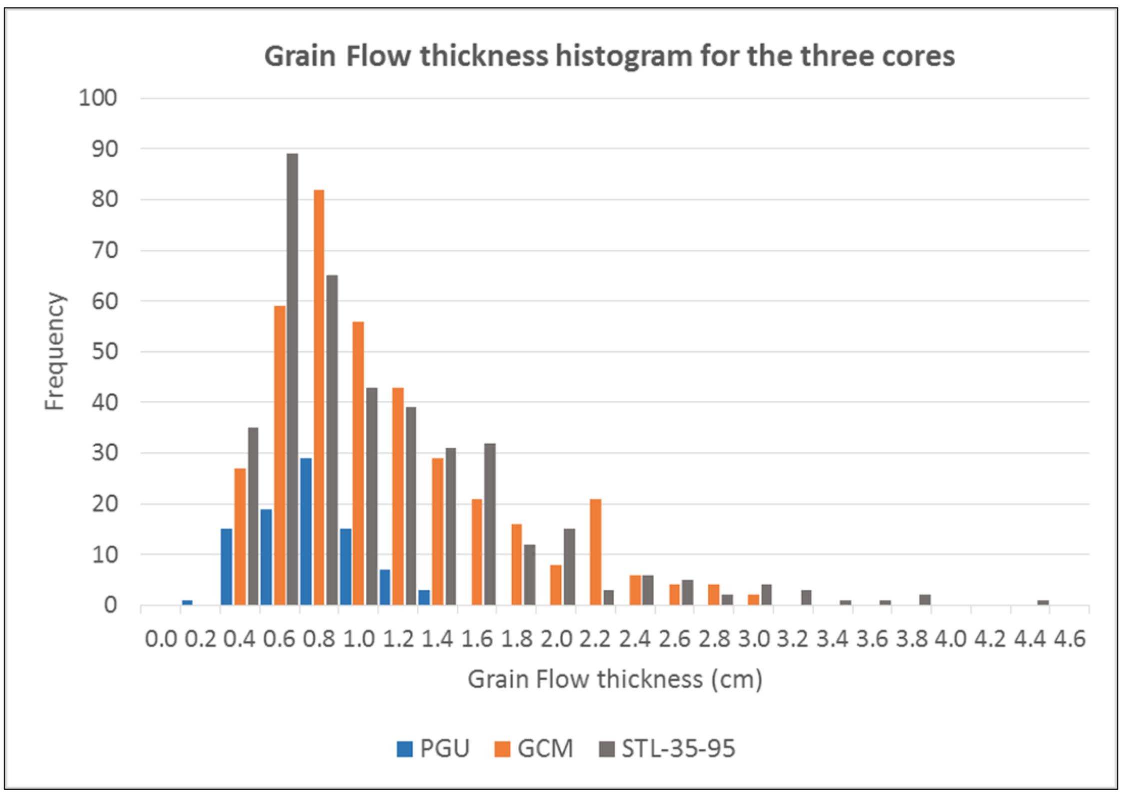


Figure 24. Grainflow thickness histogram for the three cores. Blue bars represent the updip well PGU-19-4, orange bars depict core GCM-35-11 and gray bars correspond to STL-350-95-3 in Mobile Bay. Then thinnest grainflows belong to PGU-19-4 in the updip location with the thickest grainflows being 1.4 cm thick, whereas in the other two locations most of the grainflows are 0.5 to 1.4 cm thick.

A mean of 0.99 cm grainflow thick with a standard deviation of 0.6 cm and a range from 0.2 to 4.4 cm was obtained for grainflows measured in the three cores. Grainflows from the eolian Navajo Formation and Cedar Mesa Formations in SE Utah average 2.38 cm thick with a standard deviation of 0.73 cm, and 5.47 cm with a standard deviation of 2.11 cm respectively (Romain and Mountney, 2014). Based on the data measured in this study, Norphlet Formation grainflows are thinner than those measured in Navajo and Cedar Mesa Formations by Romain and Mountey (2014).

Based on the preserved set thickness variability in the study transect, the hypothesis of the increase of eolian set thickness and decrease in bounding surfaces moving away from its source was confirmed in the study area as is shown in a histogram with preserved set thickness for each core (figure 25). The blue bars represent PGU 19-4 core, located in the upwind margin of the ancient dune field, where due to fluvial and eolian interactions, the resulting sets are thinner, produced by multiple depositional processes: fluvial and eolian interactions. In contrast, locations GCM-35-11 and STL-350-95-3 have thicker preserved eolian sets, with a big portion located around 1.5 to 4 m. The well STL-350-95-3 in Mobile Bay area shows the thickest preserved dune sets as well as the largest formation thickness.

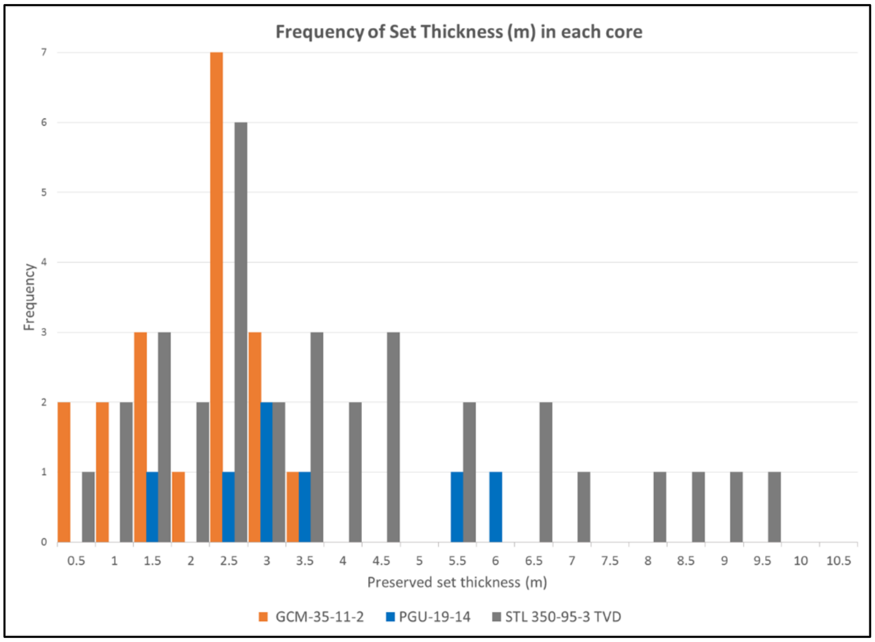


Figure 25. Histogram comparing preserved set thickness (m) for the three cores. Blue bars represent PGU-19-4 core, orange bars GCM-35-11-2 core and gray bars STL-350-95-3 core. Thickness corrected by deviation in STL-350-95-3.

The meaning of preserved set thickness either in fluvial and eolian deposits is a topic of debate (Paola and Borgman, 1991; Kocurek and Crabaugh, 1993). For climbing eolian bedforms that migrate more than one spacing during deposition, the preserved set thickness is a fraction of dune height (Rubin and Hunter, 1982). In the former case, the original thickness of the eolian set is controlled by the angle of climb and also by the bedform wavelength or size (Rubin, 1987).

A positive relationship between preserved set thickness and dune wavelength was reported by Romain and Mountney (2014) in eolian deposits of Cedar Mesa and Navajo sandstones, the authors indicates that similar climbing angles for the measured sections of both systems, might have generated similar values in the coefficient that relates these two parameters (Cedar Mesa Sandstone R^2=0.61 and Navajo Sandstone R^2=0.78). Due to the nature of the subsurface data in this study, the climbing angle cannot be measured in core, since cores do not provide lateral continuity. Assuming that in GCM-35-11-2 and STL-350-95-3, similar climbing angles occurred during deposition, thicker dunes were deposited in Mobile Bay area than in Hatters Pond. In this last location (core GCM-35-11-2), the density of the minor bounding surfaces (reactivation surfaces), suggests common re-orientation and scouring of the dunes that might be associated to a more dynamic area of the dune field potentially controlled by sediment availability.

In addition to the distance from the sediment source, other parameters that might have contributed to the increase in set thickness for Mobile Bay location are: higher subsidence and pre-existing structural features like grabens with underlying evaporitic deposits that shielded dunes deposits preserving morphology of the dunes. Isopach maps from 3D seismic in Mobile Bay and Fairway Field in offshore Alabama support the idea of linear dunes in these locations reaching up to 500 ft (Story, 1998; Taylor et al., 2004; Ajdukiewicz, et al., 2010)

5.2 Relationship between set thickness and grainflow thickness

Cross plots between set thickness (defined by 1st order BS) and grainflow thickness for each location were performed with the aim to identify any relationship between these parameters and relate them to relative dune size. In the updip location the range of grainflow thickness is basically the same either thin or thick sets (figure 26). In this case, this core has limited data points, since only three sets contain grainflows and also because thin eolian intervals are interbedded with fluvial deposits in this location.

For the intermediate location (GCM-35-11-2) cross plot, there is not a linear relationship between grainflow thickness and eolian set thickness, but rather an increase in the range of the grainflow thickness as the sets become thicker (figure 26). For example a set of 2.4 m thick, contains grainflows from 0.2 to 2.8 cm thick; in contrast a set of 0.4 m has grainflows from 0.5 to 1.2 cm. One explanation for this observation, is that thicker sets might represent larger dunes (Kocurek and Dott, 1981), in which a higher fraction of lee face is preserved, covering part of the dune toe (thinner grainflows) and also middle and upper dune section that contains thicker grainflows. Whereas thinner sets, might indicate thinner preserved dune sections (commonly the basal section), in which a narrower range of grainflows are kept in the rock record.

In the farthest location (core STL-350-95-3) the cross plot also does not show a linear relationship. But an interesting observation is that the widest range of grainflow thickness are contained in sets between 1.5 to 2.2 m thick (figure 26). These set thickness are similar to location GCM-35-11-2, where a broader range of grainflow are preserved. Eolian set and grainflow thickness do not necessarily show a good correlation for various reasons: angle of climb also controls dune size, measure sets and grainflow might not correspond to the central through of the dune (specially in cores), since cores might be cutting clipping edges of the grainflow, and sets tend to preserve the lowermost section of the dune where grainflow toes are common and thinner (Romain and Mountney, 2014 their figure 10).

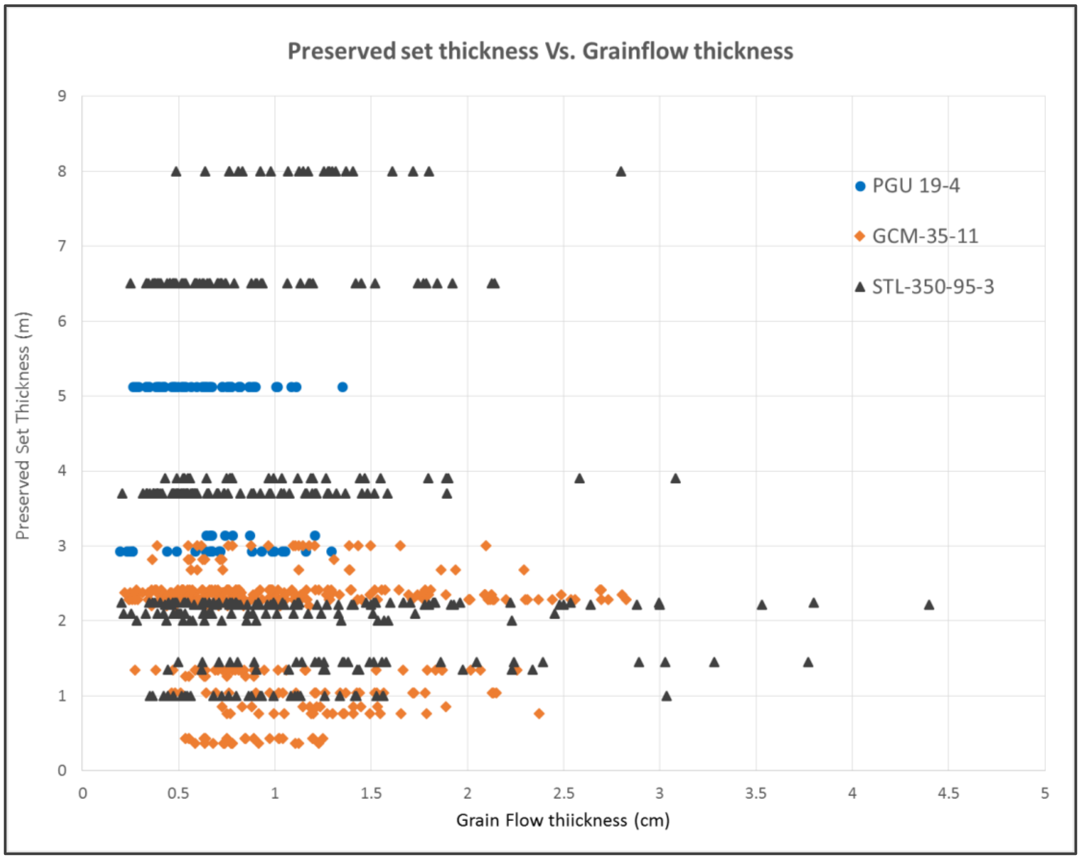


Figure 26. Cross plot between grainflow thickness (cm) and set thickness (m), wells PGU-19-4 (blue circles), GCM-35-11-2 (orange diamonds), STL-350-95-3 (black diamonds).

5.3 Dune height estimation

Using previous measurements of grainflow thickness and dune slipface height of modern dunes in Little Sahara (Kocurek and Dott, 1981) and preserved grainflow thickness and estimated dune height for the eolian Navajo Formation (Romain and Mountney, 2014), an estimation of dune height for the dataset was calculated. The thickest grainflow for each main depth interval of the three cores, were plotted in a graph using the best fit equation for Kocurek and Dott (1981) dataset (figure 27). Based on this estimation, dunes in Flomaton field were around 1.4 to 1.6 m high, whereas in GCM-35-11-2 core, the estimation suggest high dunes, ranging between 3.1 to 4.9 m high. In STL-350-95-3 there are two populations of dune size, sets containing grainflows belonging to the lowermost section of the Norphlet Formation, show dunes height of 9.4 and 7.5 m, but the upper sets (belonging to the middle section of the Norphlet Formation) indicate dunes around 3.2 to 3.9 m, very similar to GCM-35-11-2; suggesting that in Mobile Bay dunes deposited during the lower section of the Norphlet Formation were significantly larger than the ones deposited during the middle and upper interval.

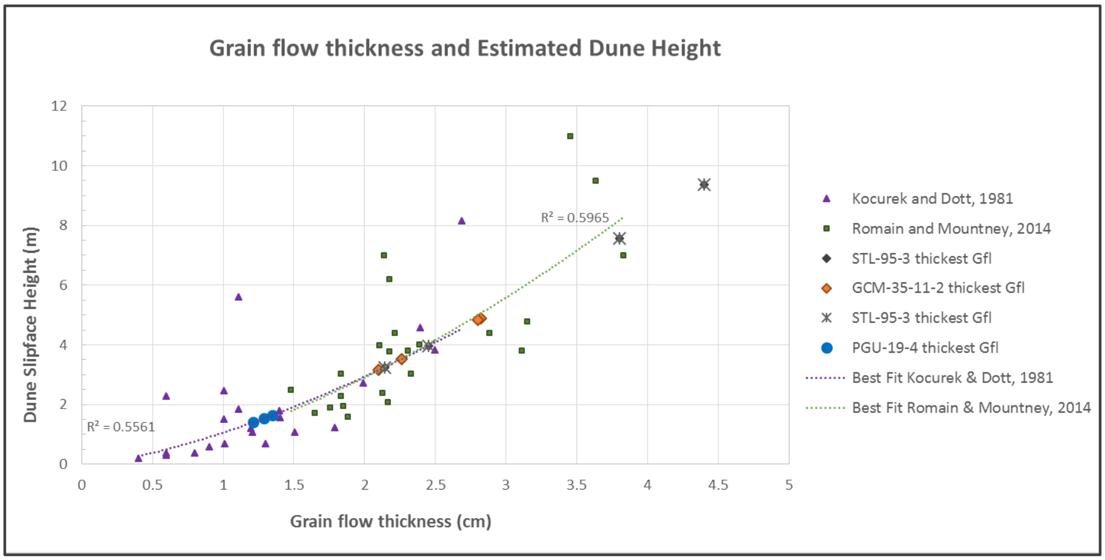


Figure 27. Dune height estimation using previous publications datasets. Purple triangles correspond to measurements of Kocurek and Dott (1981) in Little Sahara dune field, purple curve is the best fit equation of this dataset. Green squares correspond to eolian Navajo Formation grainflow measurement and dune height estimation of Romain and Mountney (2014), green line represents the best fit equation for their dataset. Blue dots correspond to the thickest grainflow measurement in three depth core intervals in PGU-19-4 core. Orange diamonds correspond to the thickest grainflow measurement in four depth core intervals in GCM-35-11 core and gray crosses represent STL-350-95-3 in four depth core intervals.

5.4 Depositional system variability and boundary conditions in the study transect

Integrating the facies and architectural eolian elements analysis performed for the three Norphlet Formation cores and the paleogeographic setting during Norphlet Formation deposition, the preserved stratigraphy indicates a system varying from a fluvial-eolian upwind margin that changes laterally to a dynamic dune field center to finally grades into a more stable linear dunes erg in Mobile Bay area.

Besides significant lateral variabilities such as facies changes from interbedded fluvial and eolian to pure eolian facies and increase in formation thickness, subtle and sharp vertical changes were recognized in the three cores. These stratigraphic variabilities represents temporal variations in the system conditions that in turn controlled the character of the vertical facies arrangement. Major vertical facies changes identified in the cores represent main bounding surfaces. For instance, in the upwind location (PGU-19-4) a bounding surface was identified in the transition from interdune to eolian deposits. This corresponds to a first order bounding surface (Kocurek, 1981). However, because of the distance between this location and the other two cores, this surface cannot be traced laterally.

Interdune facies were not recognized in GCM-35-11-2 and STL-350-95-3 cores, suggesting a dry eolian system dominated in these locations, until the upper sandsheets facies were deposited (Upper Norphlet section). Nevertheless, Mancini et al; 1985 (their figure 6-E), interpreted interdune facies in one core in Hatters Pond Field (core Getty Peter Klein 3-14 -1) at 18423-18422 ft depth, which corresponds to the lower section of the Norphlet Formation. This interpretation is based on the wavy lamination of the fine grain sandstone at that depth. Assuming that this facies corresponds to interdune facies, that transition might indicate the occurrence of another first order bounding surface from interdune-dune deposits in Hatters Pond area, but based on core GCM-35-11-2, in this area interdune intervals are rare and if present are thin (<0.5 m or 1.6 ft).

Towards the “sink” of the depositional transect, STL-350-95-3 core does not cover the basal contact between the Louann salt and the Norphlet Formation. However, Marzano (1988) and Markham (1991) reported evaporitic facies in the basal interval Mobile Bay cores, interpreted as “detrital dominated sabkha deposits”. Therefore, this contact represent the initiation of the dune field emplacement over the evaporitic deposits.

Based on the sedimentary structures observed in the cores, some climatic inferences are proposed. A wetter system was developed towards the updip location (PGU-19-4) during the deposition of the basal interval, in which interdune facies with wavy lamination, bioturbation and high siltstone content were formed, evidencing that the water table or its capillary fringe level was high and frequently in contact with the depositional surface, promoting the development and preservation of damp interdune (Kocurek and Havholm, 1993). Then the system changed to a wadi dominated system interbedded with thin eolian beds, indicating frequent floods but not very humid (e.g. coal laminae not present). On the other hand, the other two locations (Hatters Pond and Mobile Bay) indicate a dominant dryer eolian system, with virtually no interdune deposits, implying that the water table lied well below the accumulation surface and the interdune areas were reduced to isolated depressions between dunes (Kocurek and Havholm, 1993) accumulated by the train of climbing bedforms (Rubin and Hunter, 1982), leaving and preserving sets cross strata separated by interdune bounding surfaces with very thin interdune deposits, as it occur in the Namib desert today, with interdune thickness less than 5m (Lancaster and Teller, 1988).

However, in all the three locations an important facies change marked by a 1st Order BS in the upper part of the Norphlet Formation occur, in which the unit changes from fluvial–eolian dune / eolian dune facies to sandsheets facies. Although these individual surfaces are time transgressive, are yet indicating an important temporal variability in the system conditions. The predominance of sandsheets can be the result of a combination of processes: sediment availability changes, increase in sea level, and increase in water table level; and it is very likely that these factors operated at least partially interrelated. Water table level variability can be controlled by regional process such as regional changes in climate or by relative changes, for instance where accumulation progressively subside beneath a static water table (Kocurek and Havholm, 1993; Kocurek et al., 2001, Mountney, 2012).

Mathematical and physical models document that water table is significantly controlled by the variability of sea level in eolian systems, and the effects are recorded in detail in locations close to the coast, but as the distance from the coast increases, the signal of the sea level changes is subdued and only the major cycles are recognized in farthest inland locations (for distance ≥ 250 Km away from the coast) (Kocurek et al., 2001 their figure 4). In the rock record, this relationship between seal level and water table is recognizable; for example in the Jurassic Page Sandstone eolian Formation, in which major bounding surfaces and much of the minor water table controlled surfaces, indicate a progressive apparent increase in the water table, that coincide with transgressive surfaces in the adjacent Carmel sea (Kocurek et al., 2001).

In the case of the Upper Norphlet Formation, it is likely that an increase of the water table was encouraged by a general increase of the sea level, limiting the sand available to be transported by the wind, alternated with periods of sea level drop, generating some deflation and enabling available sediment to be deposited, as a consequence reworked deposition occurred in this upper interval. The increase of the sea level is even more prominent in the uppermost Norphlet section (underlying the Smackover Formation) in which the three cores show a fining upward trend that grades from fine to very fine sandstone to silty- sandstone until it grades to the marine Smackover Formation, comprised of dolomitic sandstones or dolomitic siltstone in this section.

This important change is attributed to a significant variation in boundary conditions that generated the cessation of eolian deposition and the initiation of marine sedimentation in this case tectonic is playing an important role since at the end of the Norphlet Formation deposition (Oxfordian–Kimmeridgian) the opening of the Gulf of Mexico to the Atlantic generated the filling of the Gulf and the irruption of marine waters over the Norphlet Formation erg (Salvador, 1987), producing the deposition of the overlying Smackover Formation and lower Haynesville Formation carbonates (Mancini et al., 1984)

It seems that in the study transect the change from erg to marine settings, occurred gradually because of the finning upward trend in this upper section of the Norphlet Formation, and the poor presence of eolian stratigraphic structures: grainflows, and high angle cross bedding. Instead wavy, low angle laminations and very thin grainflows were recognized.In the STL-350-950-3 core, this marine upper section below the Smackover Formation is thicker and comprised of siltstone and interpreted as marginal marine deposits, with occasional thin sand lenses, that might represent reworked eolian deposits. Nevertheless, to distinguish if regional erg deflation occurred in this transition, one would need to identify truncation of the underlying strata by the marine surface, since super surfaces typically are relatively flat and at angular discordance with the first order surfaces (Kocurek, 1988). But because the core only cover a small section of the transition Norphlet Formation- Smackover Formation, it cannot be determined. In addition, diagnosis features typical in super surfaces that have deflated to the water table, including traces of evaporites, horizons of preferential cementations and polygonal features related to salt cements (Kocurek, 1988) were not recognized in the studied cores. In cases where, super surfaces are generated by a climatic shift to humid conditions, vegetation features such as plant roots, and soil development are formed (Kocurek, 1988); however, sedimentary structures in the uppermost section of the Norphlet Formation do not indicate this process was the case.

Moreover cores do not provide the lateral continuity as an outcrop does, therefore it is hard to decipher if this contact represent a first order bounding surface or a super surface. One alternative with subsurface data, would be to analyze dense wellbore data area with high resolution image well logs and identify truncation features in these logs.

5.5 Bedding orientation and sediment pathways

For the updip location (Flomaton Field, Escambia County) the analyzed rose diagrams shows scattered directions, reflecting the interaction of the regional winds, dunes, wadis and paleo highs in this area, that also are interpreted in the stratigraphic column (fluvial and eolian interbedded deposits). A regional dipmeter analysis indicates that wells in Escambia County show a random distribution of dipping directions and no clear trend was identified (Hunt, 2013). The dipmeter well logs character might be the result of the common change in orientation of the fluvial deposits and eolian margin deposits in this sector, product of wadis incursions that brought sediment southwards from the Appalachians.

Fluvial incursions in modern dune fields play an important role providing sediments and controlling geomorphic expression of dunes, interdunes and sand sheets deposits due to long lived interactions (Al-Masrahy and Mountney, 2015). Several configurations can be recognized in fluvial-eolian systems; ephemeral rivers can penetrate the dune field with a parallel or perpendicular trend to eolian forms, bifurcation of rivers between isolated dunes can occur, fluvial incursions associated with sheets sources might occupy broad areas with poorly defined channels, and in other cases fluvial encroachment can cause cessation of dune fields (Al-Masrahy and Mountney, 2015). However, with the available data is difficult to stablish the prevailing configuration of the dunes and wadis for the Norphlet Formation during its deposition, but smaller dunes (approximately 1.5 m height) with a poorly organized pattern encroached by wadis, which transported sediment from NE (Appalachians source) is the inferred setting for Flomaton field in Escambia county. In addition it is documented that this fluvial-eolian system was connected to an alluvial fan complex located at the toe of the highlands (Wilkerson, 1981; Mancini et al. 1985; Ridgway, 2010; Hunt, 2013) rimming the margin of the Norphlet erg in the E-NE area (figure 28).

In Hatters Pond field (updip- intermediate location) the main foreset strata show a dipping trend towards the SW, in agreement with Hunt, (2013). Since foreset strata does not present an important vertical variability, dune migration pattern was similar in time in this location, suggesting a narrow range of transport direction, associated to wind direction (toward SW) and potentially more organized dune patterns. The exact shape of the dunes complex is hard to determine in this location, since no public seismic data was available, but from the set thickness and grainflow thickness analyses, dunes in this area were bigger than in Flomaton field; and using modern dunes relationships between maximum grain one can infer an original dune height around 3 to 5 m for Hatters Pond Area.

In the sedimentary sink of this transect the Norphlet Formation is composed by mainly eolian dune deposits, therefore bedding orientation can be associated to the dunes migration direction. For Mobile Bay area the dipmeter data indicates a dune migration direction E-SE (figure 28), inferring a predominant wind direction in the same direction. Based on their preserved set thicknesses and estimated height, these dunes are interpreted to be deposited in organized pattern, with higher spacing between crest and crest but larger dunes (7-9 m in the lower Norphlet Formation section and 3 to 4 m in the middle section). This interpretation is consistent with the linear dune complex interpreted from seismic and well data: linear dunes elongated NW-SE direction (Story, 1998; Taylor et al., 2004; Ajdukiewicz, et al., 2010).

Regional paleo-circulation models for Late Jurassic in North-America, propose that summer wind directions for this area were NE with a winter SW component (Parris and Peterson, 1988). However, wind predictions from these models show good correlation with eolian formations in the Western Interior of North America, but not for the Gulf Coast region (Peterson, 1988). Dipmeter data from the Norphlet Formation in Alabama suggest variable transport directions, related to the proximity to the arches (Conecuh and Wiggins Arches), but with predominance S-SW direction and it shifts in Mobile Bay towards S- SE (figure 28); another valid interpretation is that the winter wind component had a significant influence in Southwestern Alabama.

The interplay among pre-existing structures, underlying salt thickness and the paleogeographic features controlled in significant manner the orientation and distribution of the wadis and dunes orientation in the studied area and therefore the preserved stratigraphy architecture in the Norphlet Formation. Preexisting grabens might have acted as funnels, channelizing the ephemeral rivers in the updip areas.

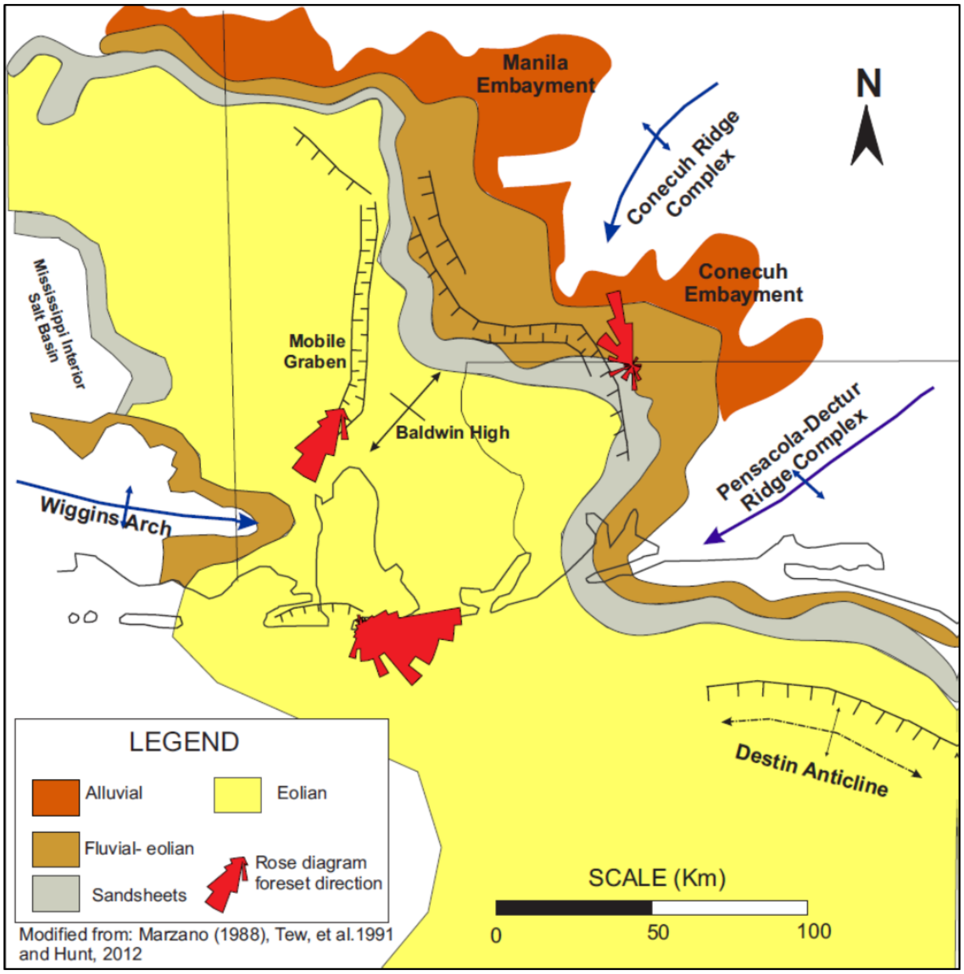


Figure 28. Regional facies map for the Norphlet Formation in Alabama with main arches and grabens. Rose diagrams considered in this study are plotted in each location in red. Modified from Marzano (1988); Tew, et al. (1991) and Hunt (2013).

Seismic data in Mobile Bay area suggests that preexisting basement structure created differential salt thickness, the thinner zones could serve as cradles for the amalgamated dunes, and the differential density probably allowed the Norphlet Formation dunes to sink into the Louann Salt once that they reached a significant thickness (around 500 m) and then became more stable for subsequent accumulation (Story, 1998). Moreover, grabens might encourage thicker salt deposition during Louann Salt deposition and might create salt mini-basins (Banham and Mountney, 2013). The interactions between the updip fluvial Norphlet Formation section and these “salt mini basins” it is a topic that needs to be better understood in the Louann Salt - Norphlet Formation system. Poor or not preservation of Louann Salt was documented for updip Norphlet Formation areas (Tolson et al., 1983, Mancini et al., 1985). However, during deposition these lows could represent and important control in the fluvial network as it is recognized in the linear dune pattern in Mobile Bay area.

6 CONCLUSIONS

Spatial stratigraphic variabilities recorded in the three cores indicate a system varying from a fluvial-eolian upwind margin that changes laterally to a dynamic dune field center to finally grades into a more stable linear dunes erg in Mobile Bay area.

Sharp vertical architectural changes suggest significant temporal climatic changes in the system conditions that in turn controlled vertical facies arrangement. The main boundary conditions are represented by: 1) the basal Norphlet Formation contact, representing the initiation of the dune field emplacement over the evaporitic deposits of the Louann Salt. 2) An important 1st order bounding surface that separates underlying wet interdune facies from dune deposits recognized in the updip core 3) Facies changes from dry eolian to marine deposits (supersurface?) in the upper Norphlet Formation section that represent the cessation of eolian deposition and the initiation of marine sedimentation identifiable in the three cores.

This study indicates that increase in preserved eolian set thickness and decrease in bounding surfaces moving away from the source occur. In the updip location thinner sets (2.93 to 5.5 m) are the product of fluvial and eolian depositional processes. In GCM-35-11 and STL-350-95-3 cores, thicker eolian sets are preserved (1.5 -6 m.), suggesting larger dunes deposition in these locations.

Preserved grainflow thickness show a positive correlation with the distance from the sediment paleosource, supporting the increase of dune size in the Hatters Pond and Mobile Bay area. Dune height estimation using maximum grainflow thickness indicates larger dunes in Mobile Bay deposited during the lower section of the Norphlet Formation but for the middle section dunes were similar in size to the ones located in Hatters Pond, and marginal smaller and disorganized dunes in Flomaton field.

Subtle vertical variations also indicate important conditions in the Norphlet Formation dune field. In GCM-35-11 (Hatters Pond field) the density of the reactivation surfaces, suggests common re-orientation and scouring of the dunes that may be associated to a more dynamic area of the dune field, controlled by sediment availability. Whereas in Mobile Bay these 3rd Order bounding surfaces shows larger spacing, indicating more stable dunes.

The transition from eolian to marine deposition might occur gradually, based on the thickness of this upper section and the fining upward trend that grades from fine to very fine sandstone (sandsheet deposits) to silty- sandstone until it grades to the marine dolomitic siltstone of the Smackover Formation (marine deposits). However, lateral continuity would be needed in order to determine if the upper Norphlet Formation eolian deposits are truncated by the marine section.

The relationship between grainflow thickness and preserved eolian set thickness is not linear, however a wider range of grainflow thickness were contained in thicker sets (1.5 to 3.60 m thick). In thicker sets a higher fraction of dune lee face is preserved, and a wide variety of grainflows sizes are recorded.

Foreset strata orientation from Norphlet Formation dipmeter data indicates SW bedding direction in Hatters Pond area with minor shifting direction in the upper section. In Mobile Bay two dipmeters indicate bedding direction towards the SE-E with higher vertical shifting in well STL-350-95-3. Since the Apalachian paleohighs were the main sediment source and the paleogeographic features for this transect, it is suggested that the bedding orientation represent the migration trend of the dunes for Hatters Pond and Mobile Bay. In the last location, this is consistent with public seismic data.

Core data analysis does not offer the lateral continuity of an outcrop, therefore tracing the extension of main bounding surfaces is limited. For the Norphlet Formation where only subsurface data is available; integration of high-resolution seismic data could improve our interpretations, as well as outcrop analogues. For small scale stratigraphic analyses, high-resolution image well logs from a high dense well area should be the ideal data set.

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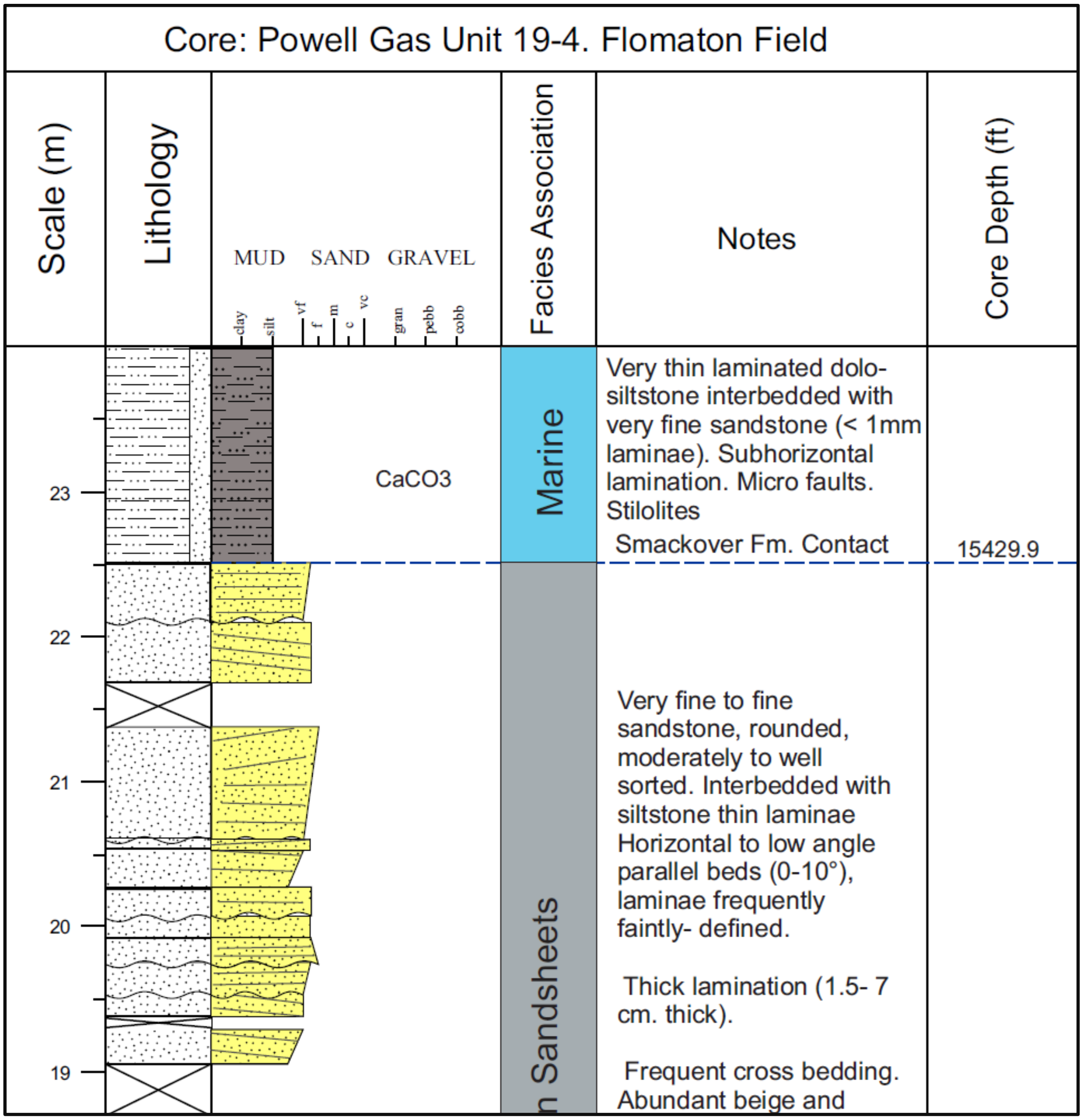
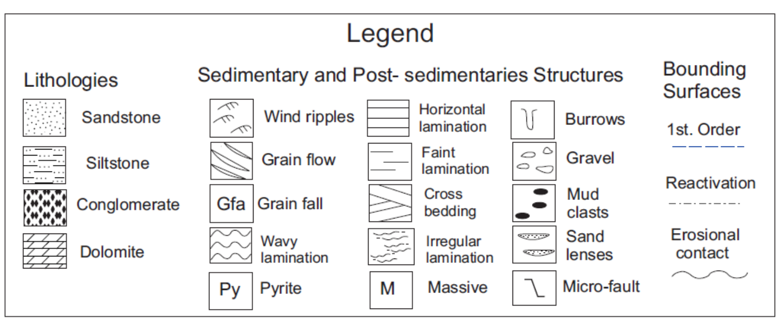
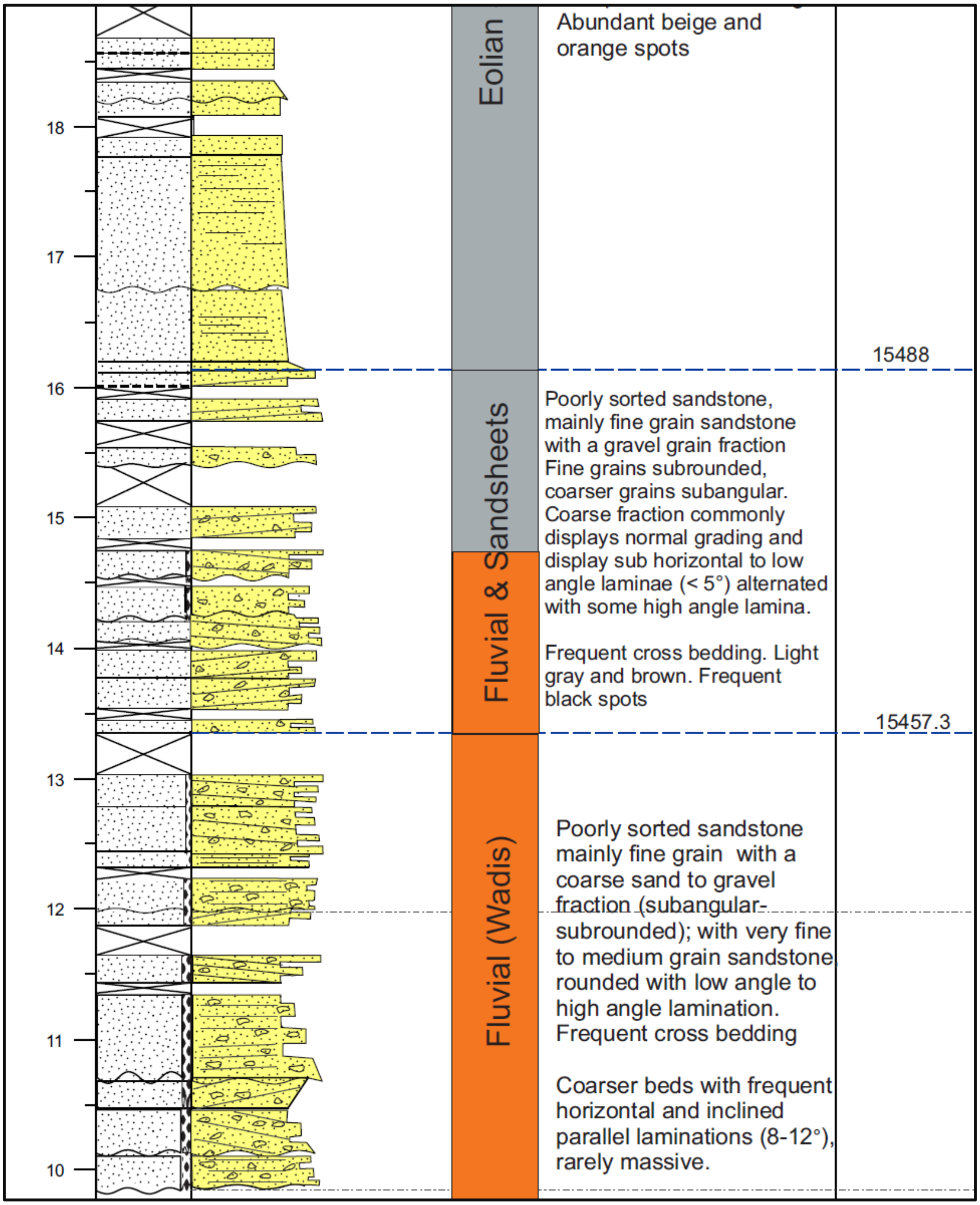
APPENDIX 1

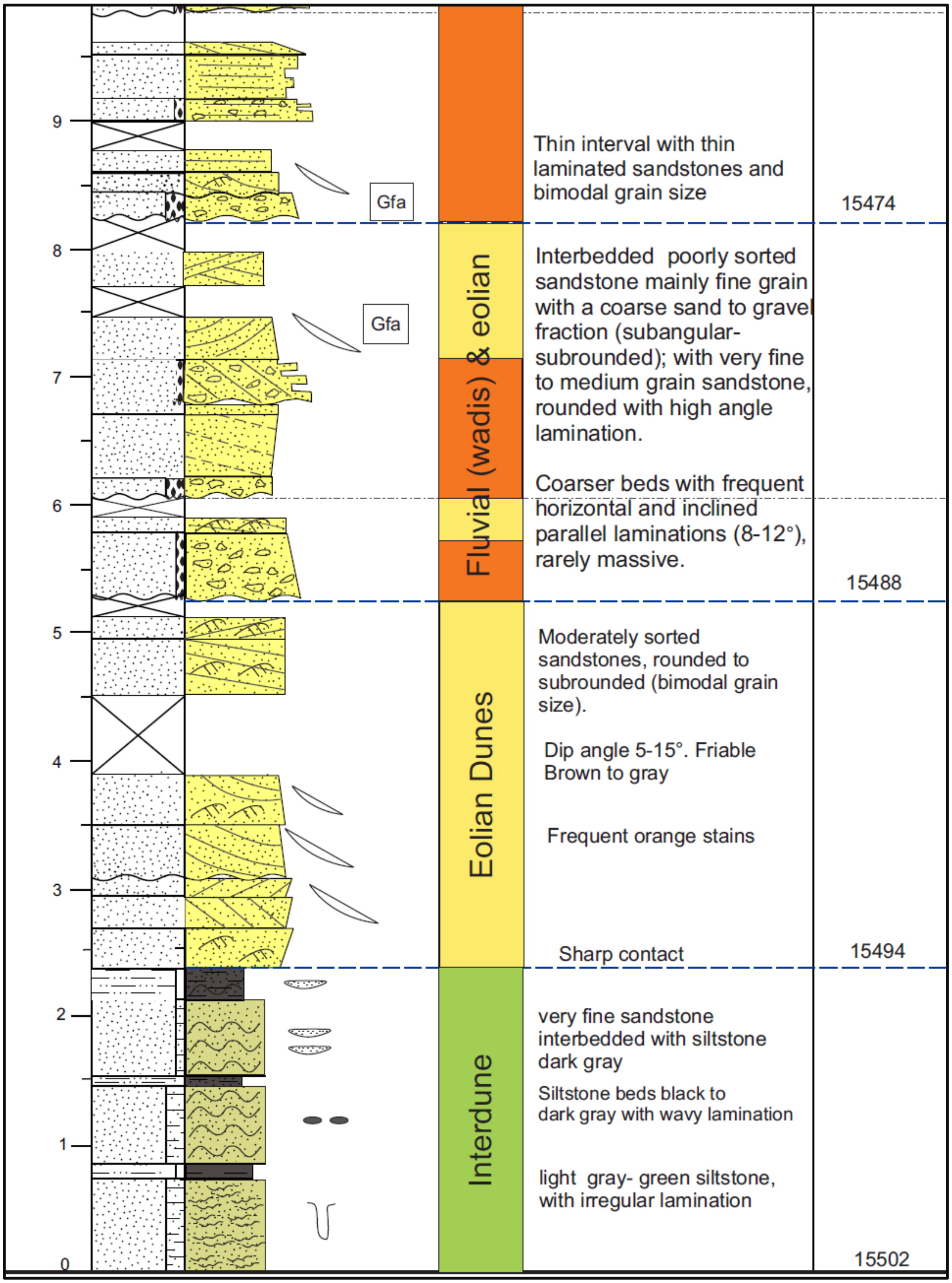


Core: Powell Gas Unit 19-4. Flomaton Field
Scale (m)
Lithology
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb
Facies Association
Notes
Core Depth (ft)
23
22
21
20
19
CaCO3
Marine
n Sandsheets
Very thin laminated dolo-siltstone interbedded with very fine sandstone (< 1mm laminae). Subhorizontal lamination. Micro faults. Stilolites
Smackover Fm. Contact
15429.9
Very fine to fine sandstone, rounded, moderately to well sorted. Interbedded with siltstone thin laminae Horizontal to low angle parallel beds (0-10°), laminae frequently faintly- defined.
Thick lamination (1.5- 7 cm. thick).
Frequent cross bedding. Abundant beige and



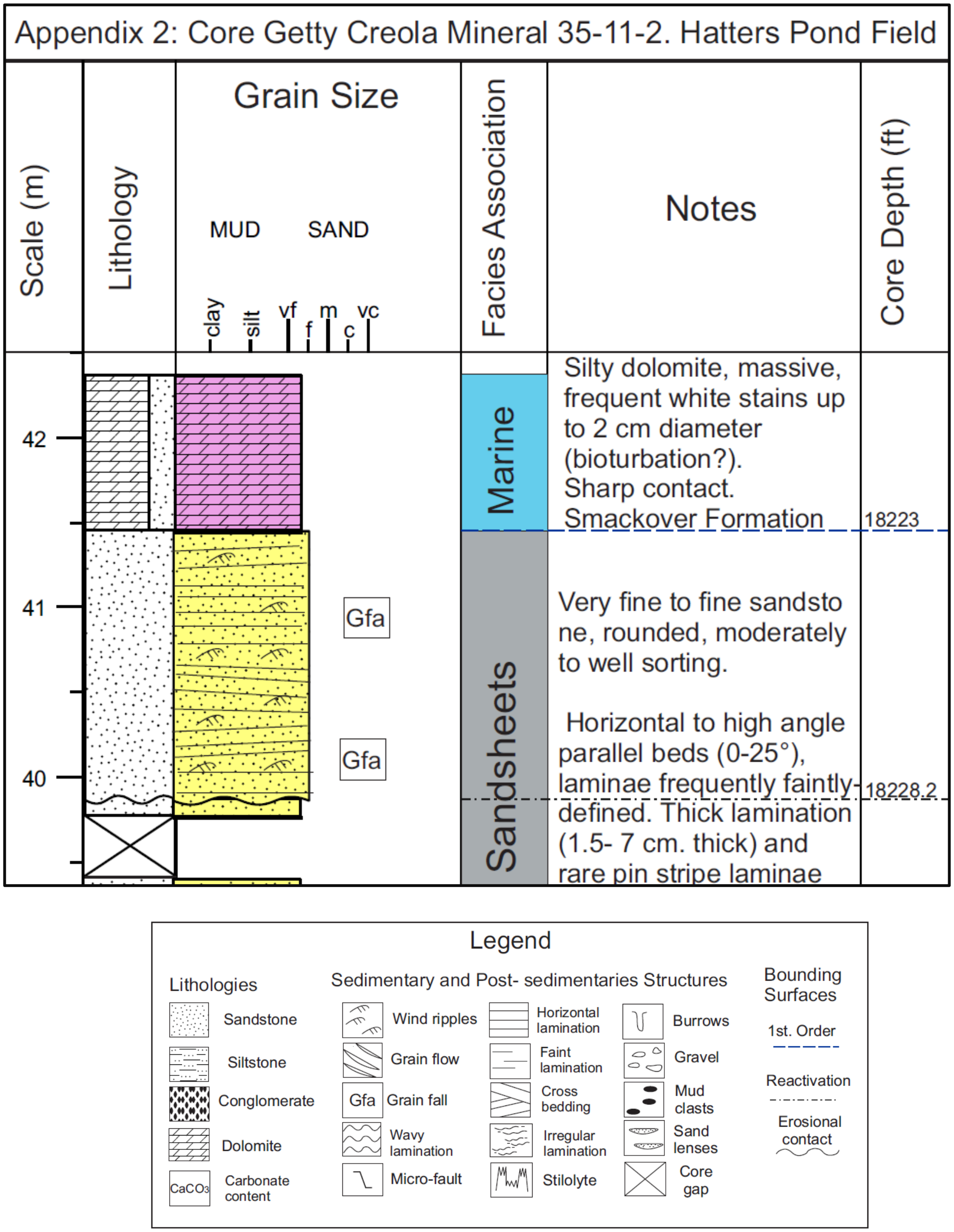
Legend
Lithologies
Sandstone
Siltstone
Conglomerate
Dolomite
Sedimentary and Post- sedimentaries Structures
Wind ripples
Grain flow
Gfa Grain fall
Wavy lamination
Py Pyrite
Horizontal lamination
Faint lamination
Cross bedding
Irregular lamination
M Massive
Burrows
Gravel
Mud clasts
Sand lenses
Micro-fault
Bounding Surfaces
1st. Order
Reactivation
Erosional contact


18
17
16
15
14
13
12
11
10
Eolian
Fluvial & Sandsheets
Fluvial (Wadis)
Abundant beige and orange spots
15488
Poorly sorted sandstone, mainly fine grain sandstone with a gravel grain fraction Fine grains subrounded, coarser grains subangular. Coarse fraction commonly displays normal grading and display sub horizontal to low angle laminae (< 5°) alternated with some high angle lamina.
Frequent cross bedding. Light gray and brown. Frequent black spots
15457.3
Poorly sorted sandstone mainly fine grain with a coarse sand to gravel fraction (subangular-subrounded); with very fine to medium grain sandstone rounded with low angle to high angle lamination. Frequent cross bedding
Coarser beds with frequent horizontal and inclined parallel laminations (8-12°), rarely massive.

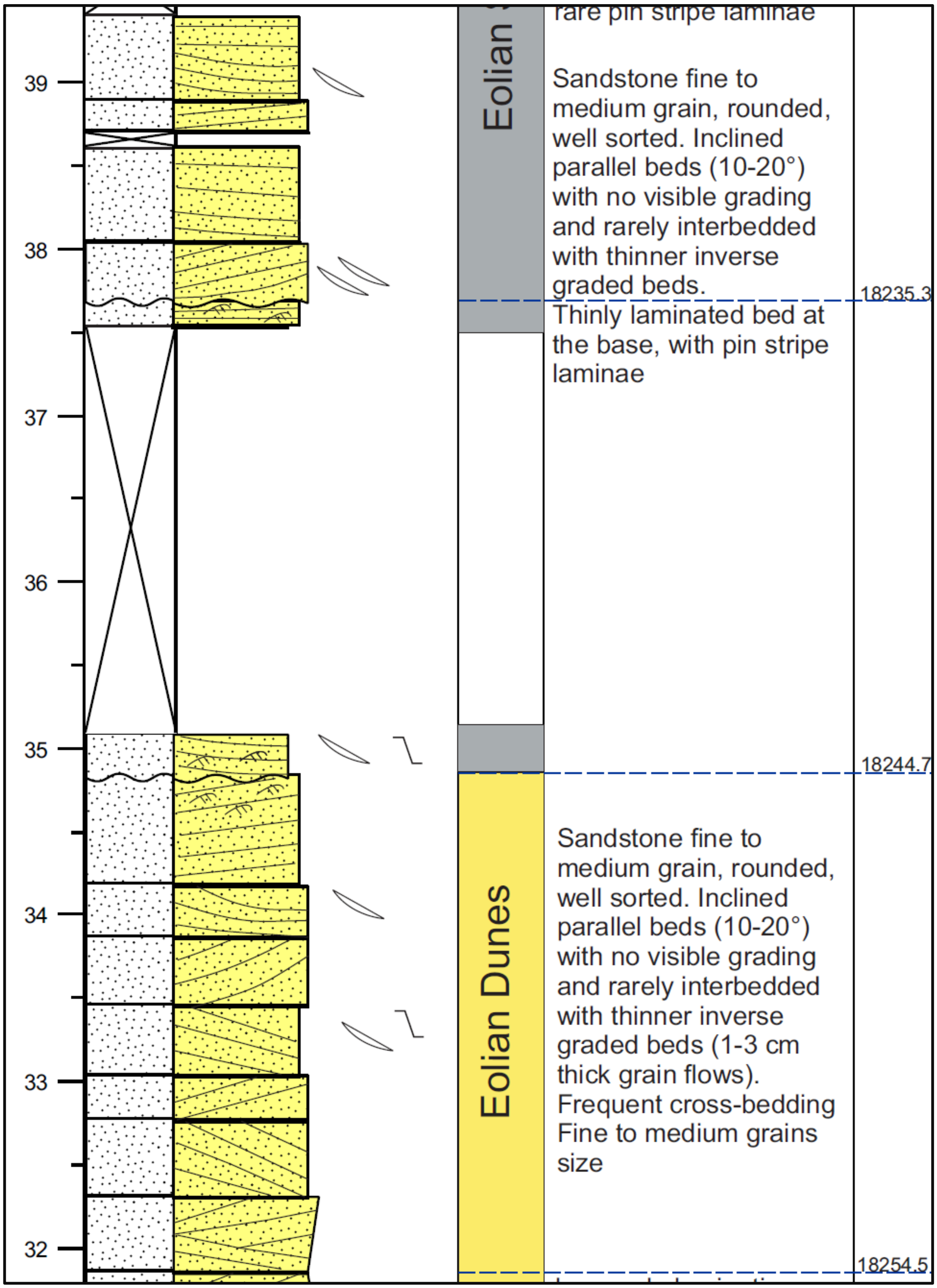


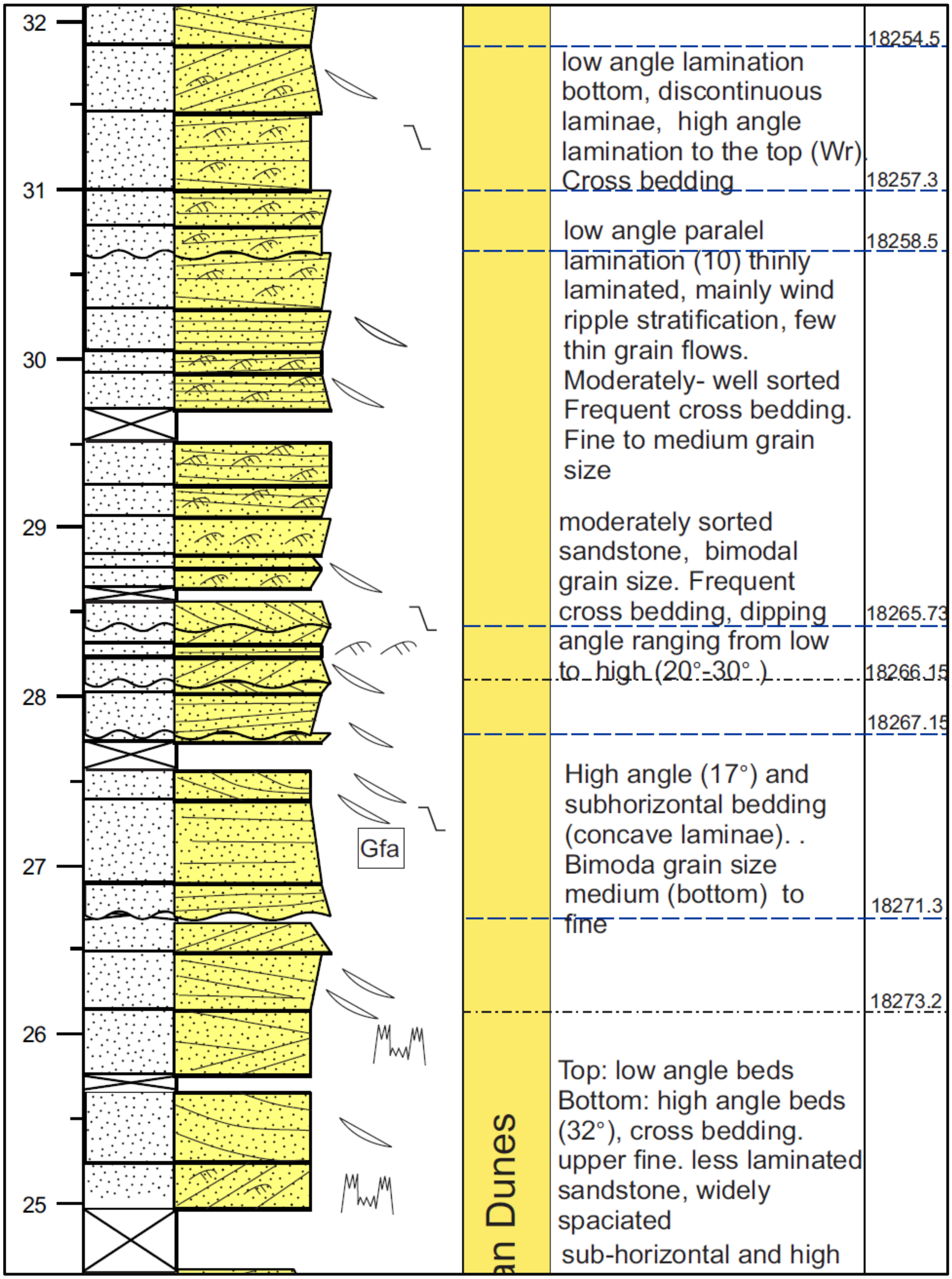
9
8
7
6
5
4
3
2
1
0
Gfa
Gfa
Fluvial (wadis) & eolian
Eolian Dunes
Interdune
Thin interval with thin laminated sandstones and bimodal grain size
15474
Interbedded poorly sorted sandstone mainly fine grain with a coarse sand to gravel fraction (subangular-subrounded); with very fine to medium grain sandstone, rounded with high angle lamination.
Coarser beds with frequent horizontal and inclined parallel laminations (8-12°), rarely massive.
15488
Moderately sorted sandstones, rounded to subrounded (bimodal grain size).
Dip angle 5-15°. Friable Brown to gray
Frequent orange stains
Sharp contact
15494
very fine sandstone interbedded with siltstone dark gray
Siltstone beds black to dark gray with wavy lamination
light gray- green siltstone, with irregular lamination
15502

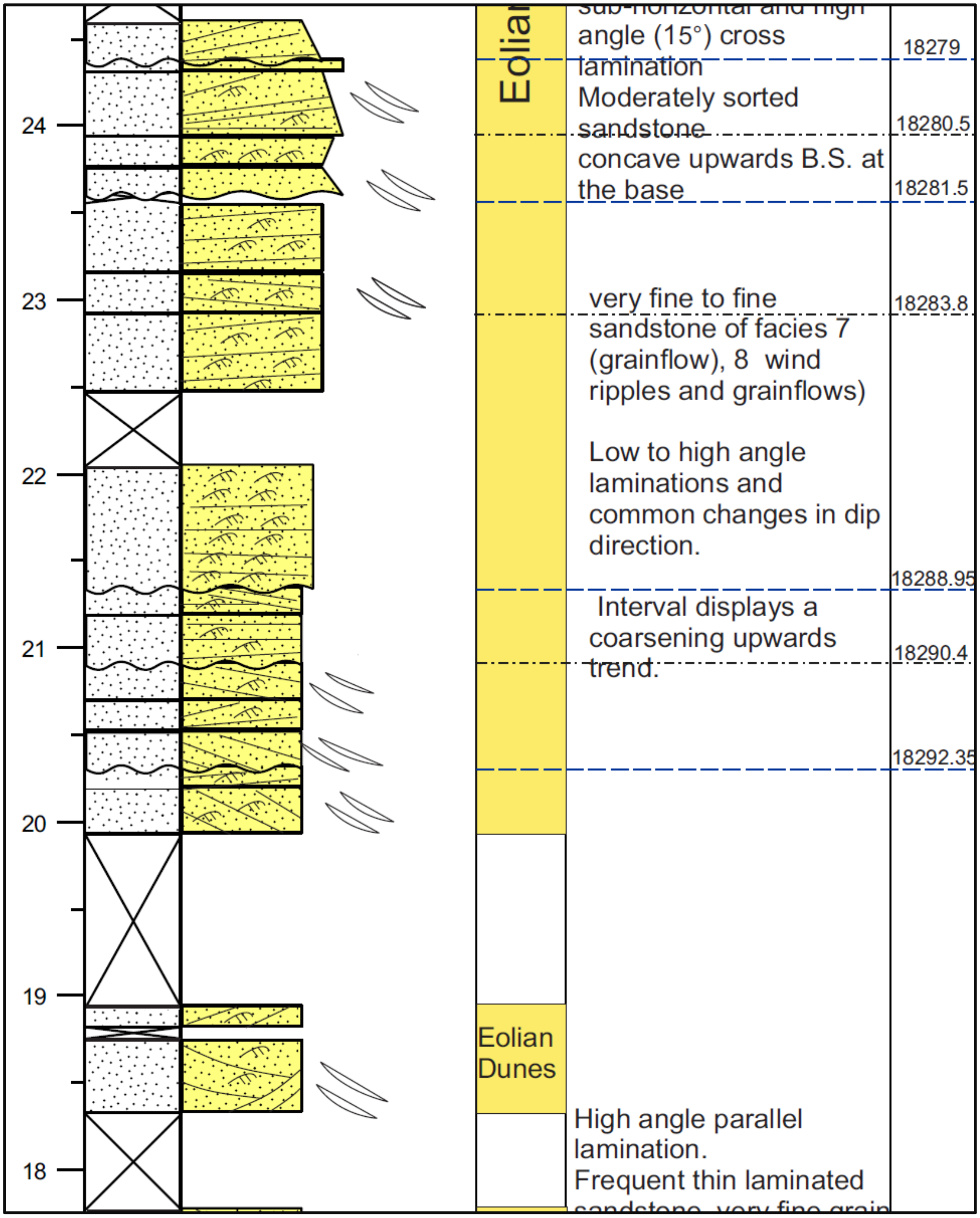
APPENDIX 2

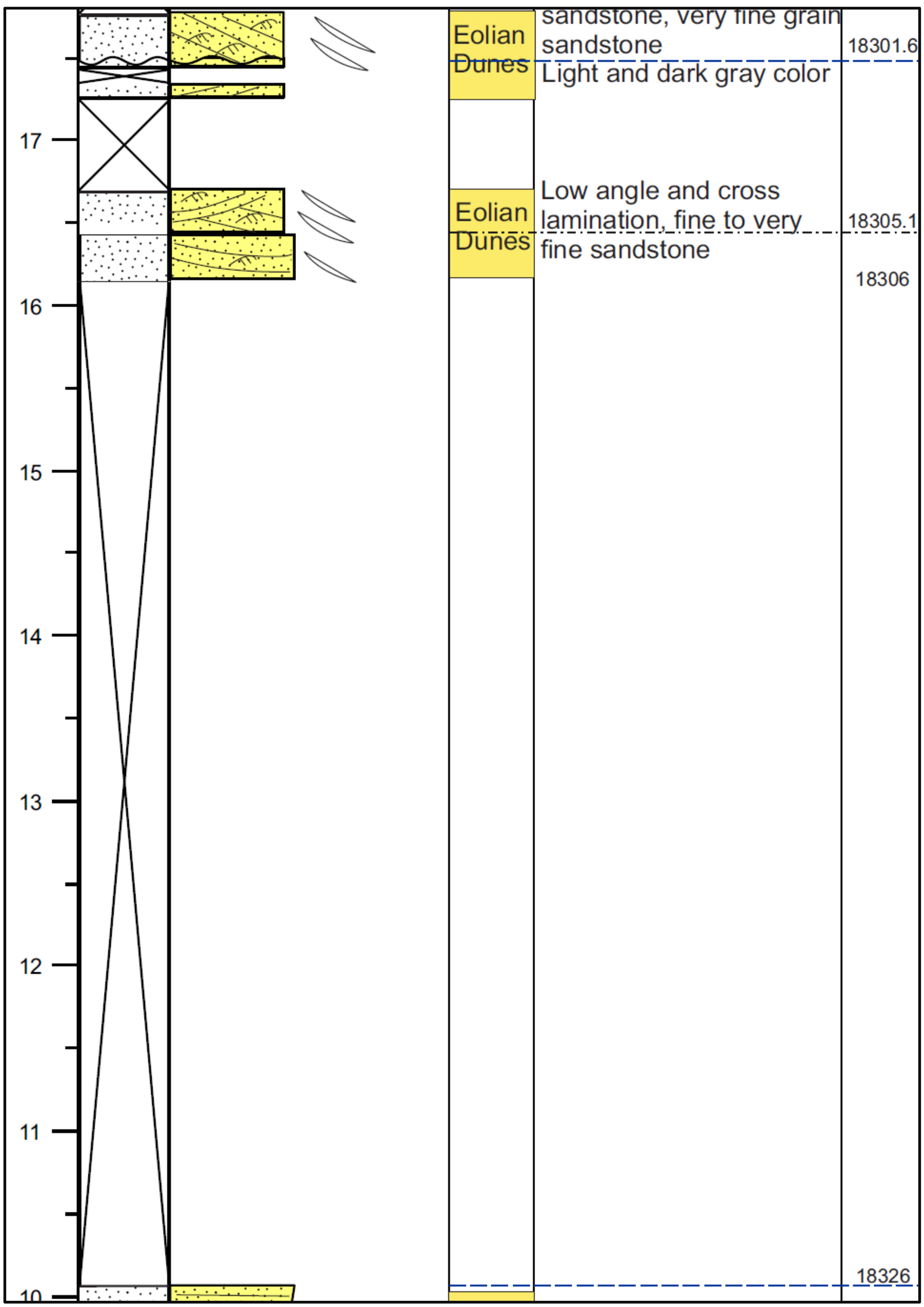


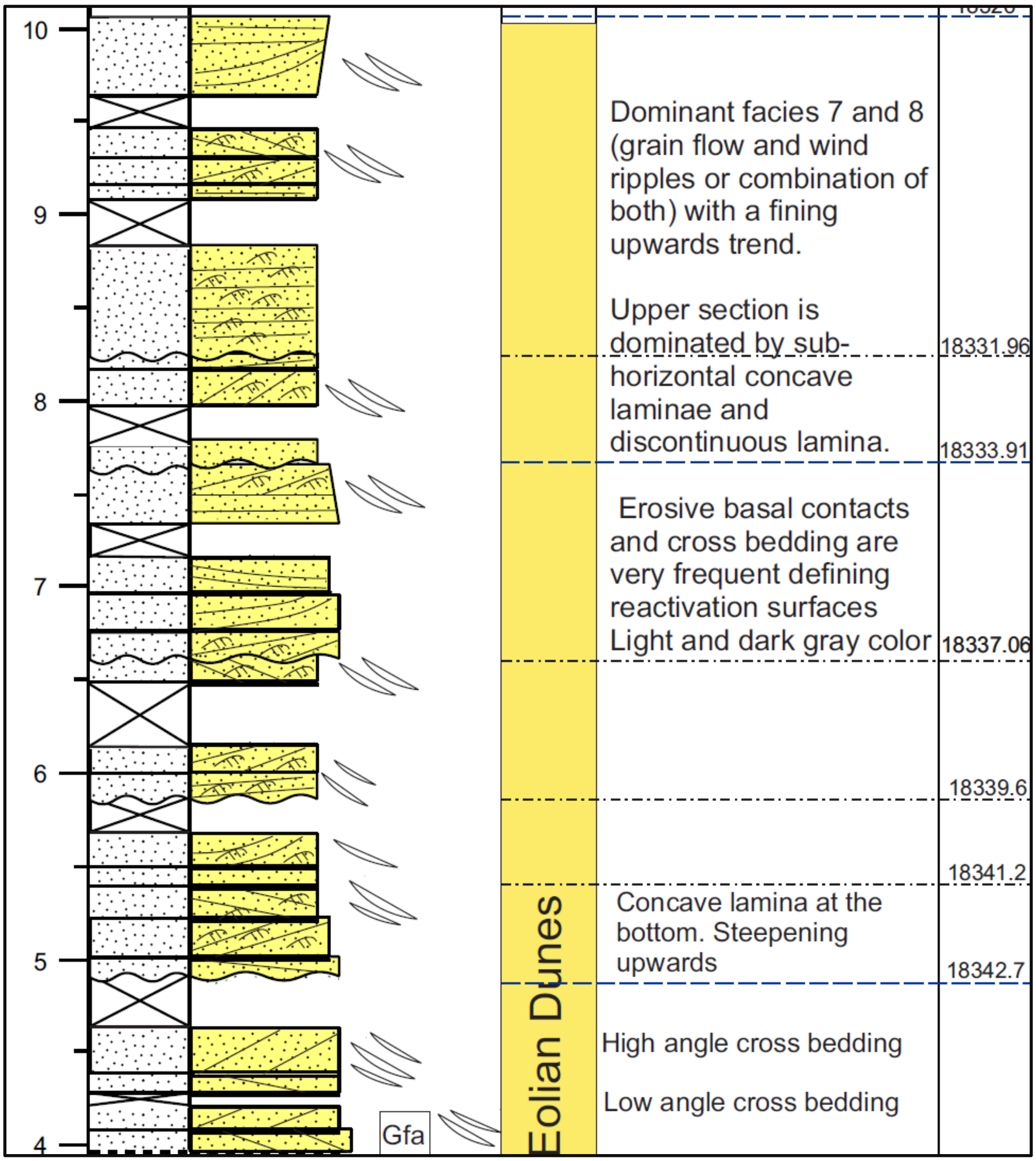
Appendix 2: Core Getty Creola Mineral 35-11-2. Hatters Pond Field
Scale (m)
Lithology
Grain Size
MUD
SAND
clay
silt
vf
f
m
c
vc
Facies Association
Notes
Core Depth (ft)
42
41
40
Marine
Sandsheets
Gfa
Gfa
Silty dolomite, massive, frequent white stains up to 2 cm diameter (bioturbation?). Sharp contact. Smackover Formation
18223
Very fine to fine sandstone, rounded, moderately to well sorting.
Horizontal to high angle parallel beds (0-25°), laminae frequently faintly-defined. Thick lamination (1.5- 7 cm. thick) and rare pin stripe laminae
18228.2
Legend
Lithologies
Sandstone
Siltstone
Conglomerate
Dolomite
CaCO3
Carbonate content
Sedimentary and Post- sedimentaries Structures
Wind ripples
Grain flow
Gfa
Grain fall
Wavy lamination
Micro-fault
Horizontal lamination
Faint lamination
Cross bedding
Irregular lamination
Stilolyte
Burrows
Gravel
Mud clasts
Sand lenses
Core gap
Bounding Surfaces
1st. Order
Reactivation
Erosional contact

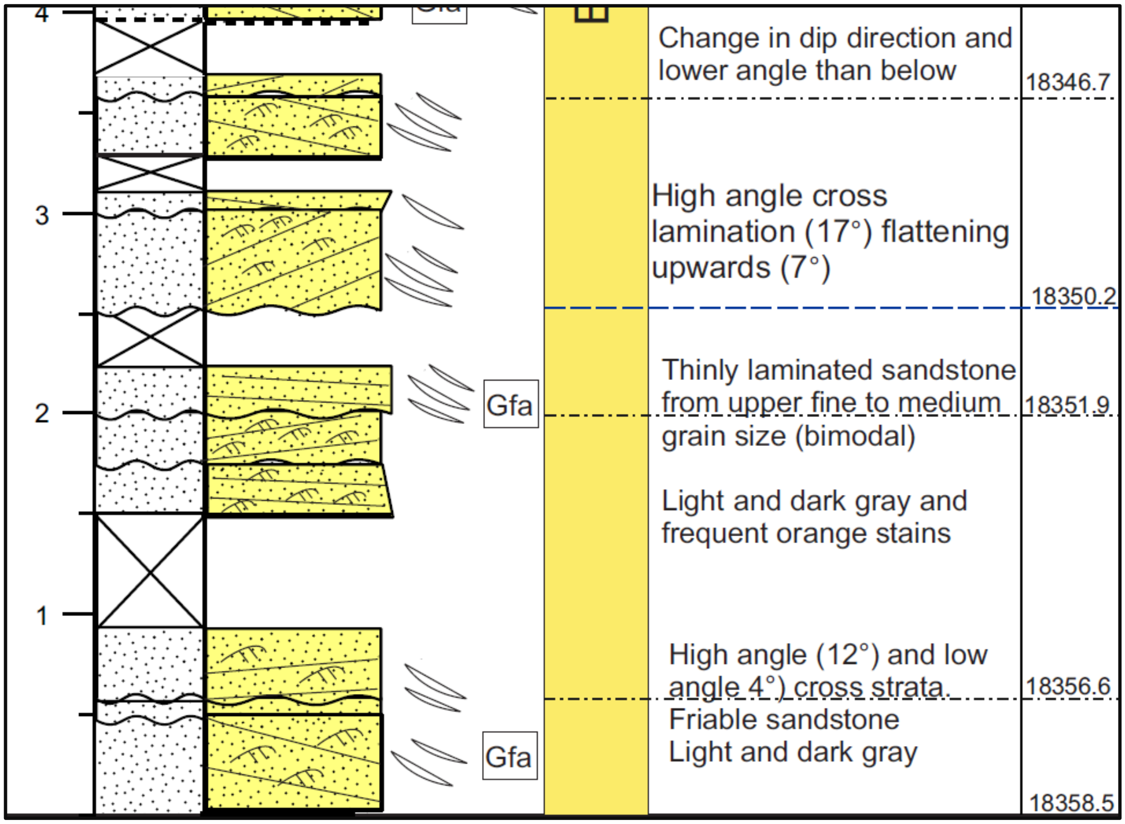

39
38
37
36
35
34
33
32
Eolian
rare pin stripe laminae
Sandstone fine to medium grain, rounded, well sorted. Inclined parallel beds (10-20°) with no visible grading and rarely interbedded with thinner inverse graded beds.
Thinly laminated bed at the base, with pin stripe laminae
18235.3
18244.7
Eolian Dunes
Sandstone fine to medium grain, rounded, well sorted. Inclined parallel beds (10-20°) with no visible grading and rarely interbedded with thinner inverse graded beds (1-3 cm thick grain flows). Frequent cross-bedding Fine to medium grains size
18254.5


32
31
30
29
28
27
26
25
Gfa
an Dunes
18254.5
low angle lamination bottom, discontinuous laminae, high angle lamination to the top (Wr). Cross bedding
18257.3
low angle paralel lamination (10) thinly laminated, mainly wind ripple stratification, few thin grain flows. Moderately- well sorted Frequent cross bedding. Fine to medium grain size
18258.5
moderately sorted sandstone, bimodal grain size. Frequent cross bedding, dipping angle ranging from low to high (20°-30°)
18265.73
18266.15
18267.15
High angle (17°) and subhorizontal bedding (concave laminae). . Bimoda grain size medium (bottom) to fine
18271.3
18273.2
Top: low angle beds Bottom: high angle beds (32°), cross bedding. upper fine. less laminated sandstone, widely spaciated
sub-horizontal and high

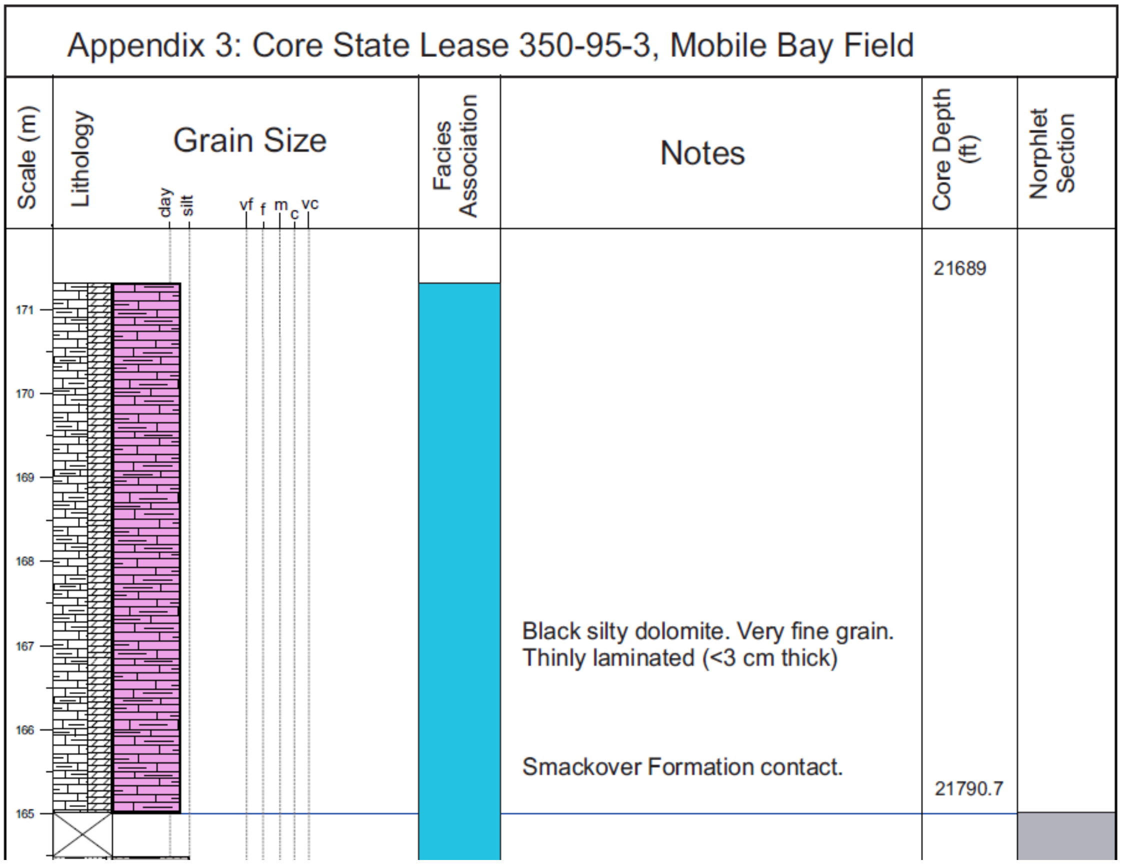

24
23
22
21
20
19
18
Eolian
Eolian
Dunes
angle (15°) cross
lamination
Moderately sorted
sandstone
concave upwards B.S. at
the base
very fine to fine
sandstone of facies 7
(grainflow), 8 wind
ripples and grainflows)
Low to high angle
laminations and
common changes in dip
direction.
Interval displays a
coarsening upwards
trend.
High angle parallel
lamination.
Frequent thin laminated
18279
18280.5
18281.5
18283.8
18288.95
18290.4
18292.35


sandstone, very fine grain
sandstone
Light and dark gray color
Eolian Dunes
18301.6
17
Low angle and cross
lamination, fine to very
fine sandstone
Eolian Dunes
18305.1
18306
16
15
14
13
12
11
18326
10

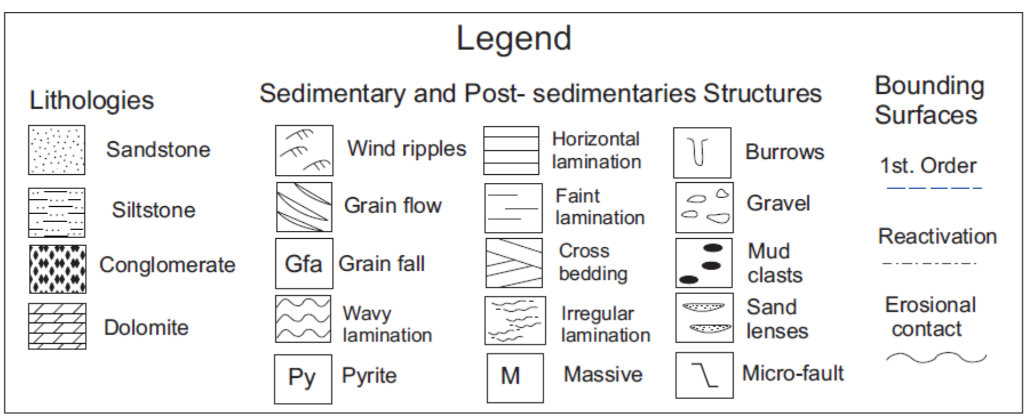

10
9
8
7
6
5
4
Gfa
Eolian Dunes
Dominant facies 7 and 8 (grain flow and wind ripples or combination of both) with a fining upwards trend.
Upper section is dominated by sub-horizontal concave laminae and discontinuous lamina.
Erosive basal contacts and cross bedding are very frequent defining reactivation surfaces Light and dark gray color
Concave lamina at the bottom. Steepening upwards
High angle cross bedding
Low angle cross bedding
18331.96
18333.91
18337.06
18339.6
18341.2
18342.7


4
3
2
1
Gfa
Gfa
Change in dip direction and lower angle than below
18346.7
High angle cross lamination (17°) flattening upwards (7°)
18350.2
Thinly laminated sandstone from upper fine to medium grain size (bimodal)
18351.9
Light and dark gray and frequent orange stains
High angle (12°) and low angle 4°) cross strata
18356.6
Friable sandstone
Light and dark gray
18358.5

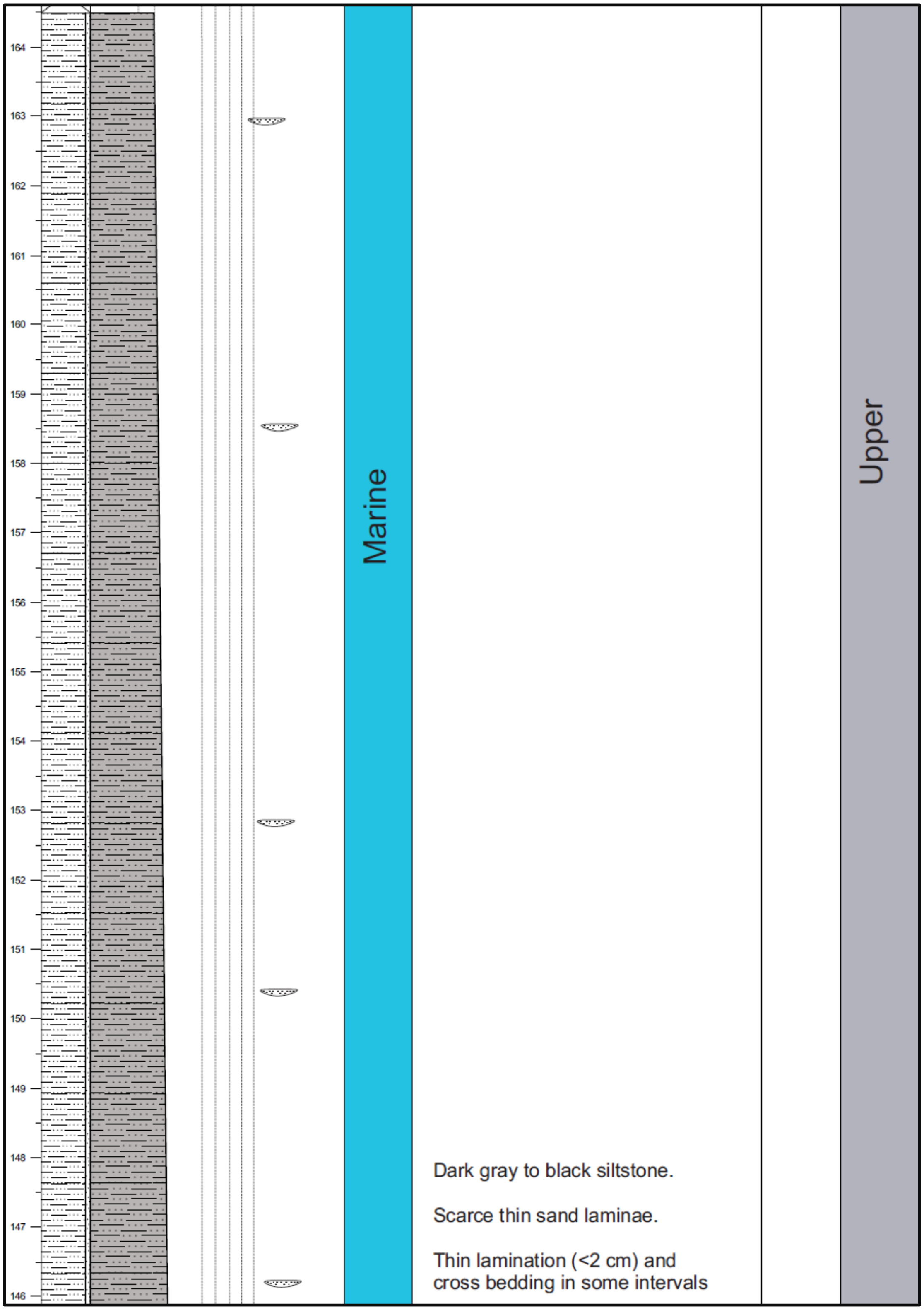
APPENDIX 3

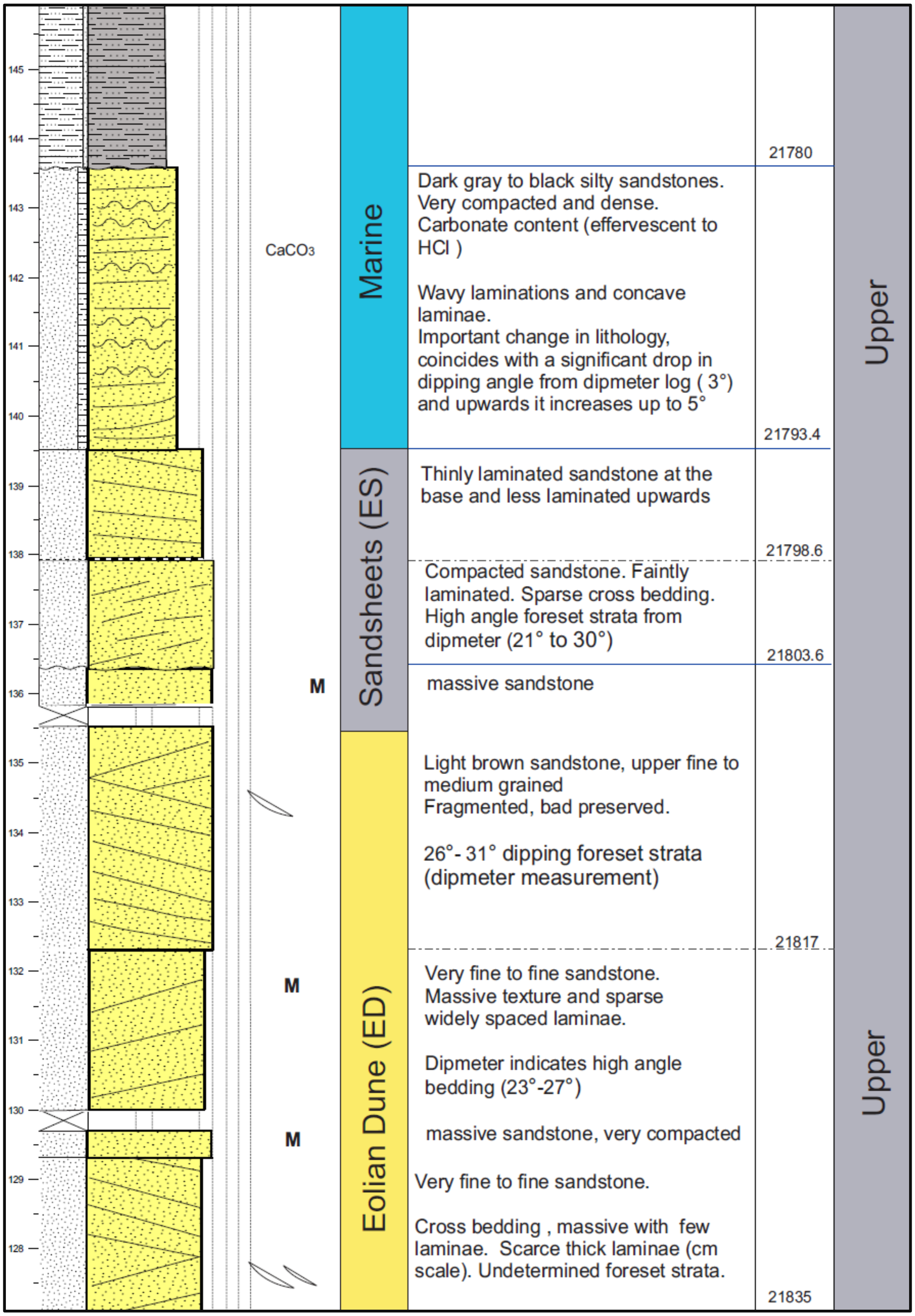


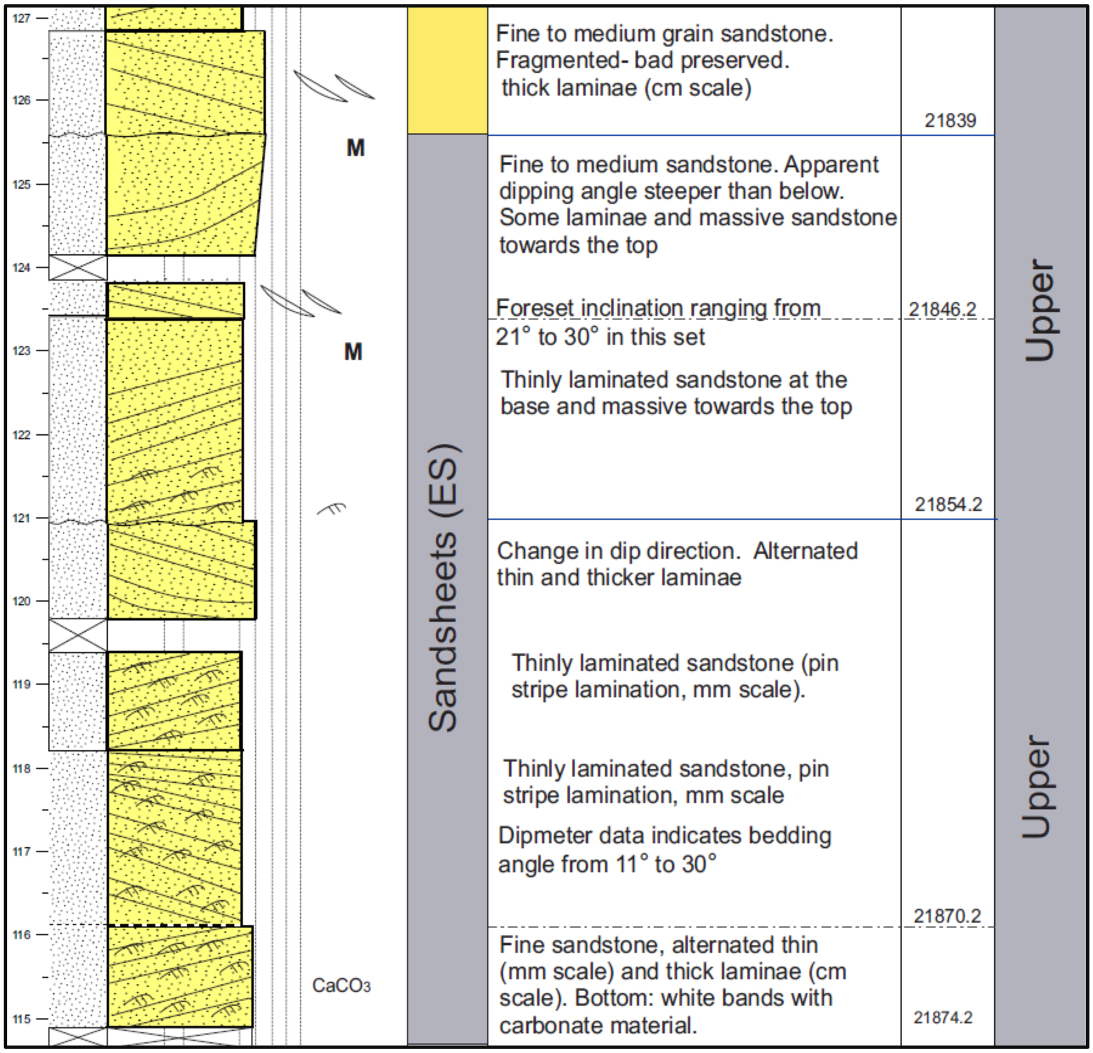
Appendix 3: Core State Lease 350-95-3, Mobile Bay Field
Scale (m)
Lithology
Grain Size
clay
silt
vf
f
m
c
vc
Facies Association
Notes
Core Depth (ft)
Norphlet Section
21689
171
170
169
168
167
166
165
Black silty dolomite. Very fine grain. Thinly laminated (<3 cm thick)
Smackover Formation contact.
21790.7

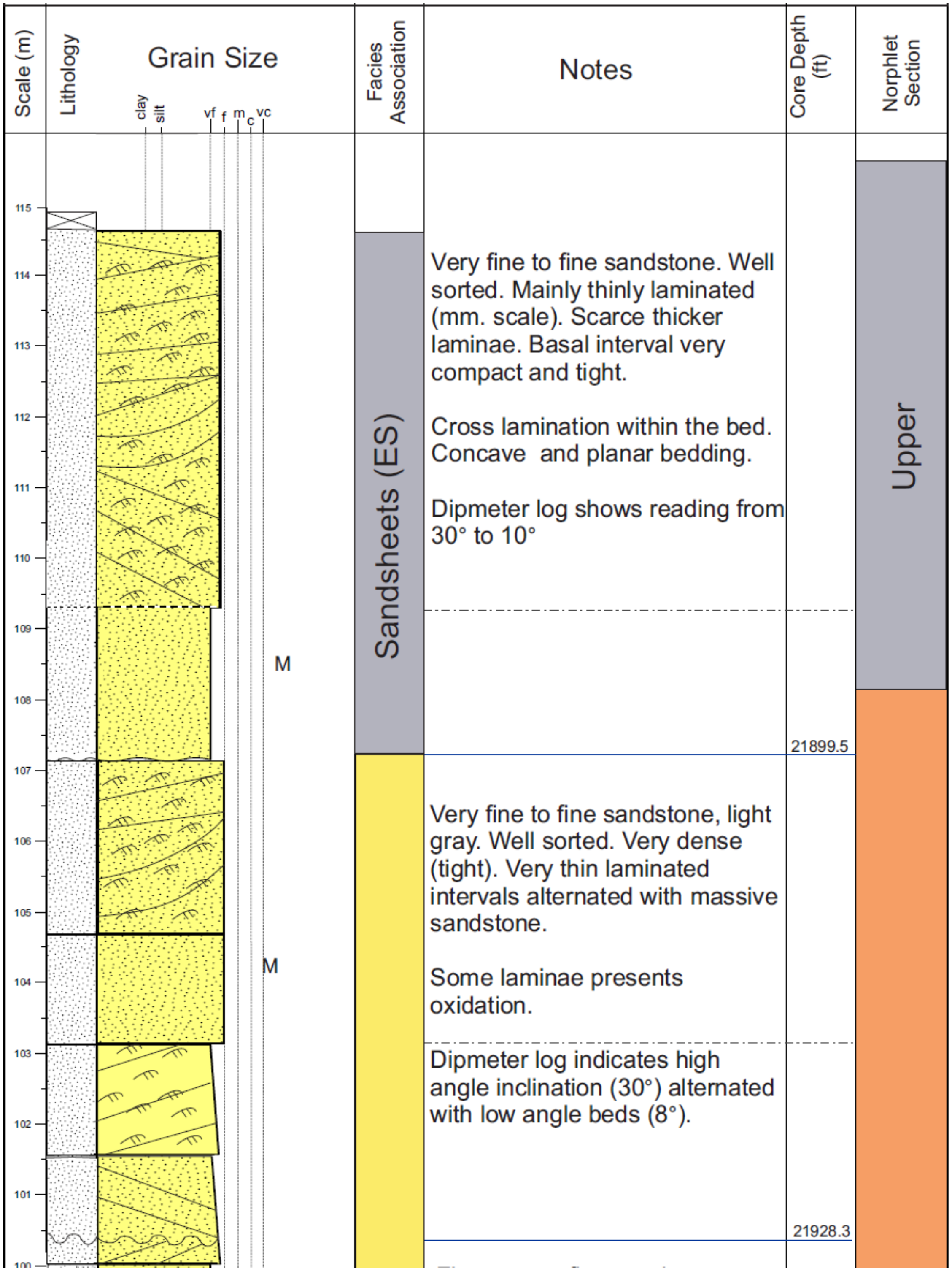


Legend
Lithologies
Sandstone
Siltstone
Conglomerate
Dolomite
Sedimentary and Post- sedimentaries Structures
Wind ripples
Grain flow
Gfa
Grain fall
Wavy lamination
Py
Pyrite
Horizontal lamination
Faint lamination
Cross bedding
Irregular lamination
M
Massive
Burrows
Gravel
Mud clasts
Sand lenses
Micro-fault
Bounding Surfaces
1st. Order
Reactivation
Erosional contact

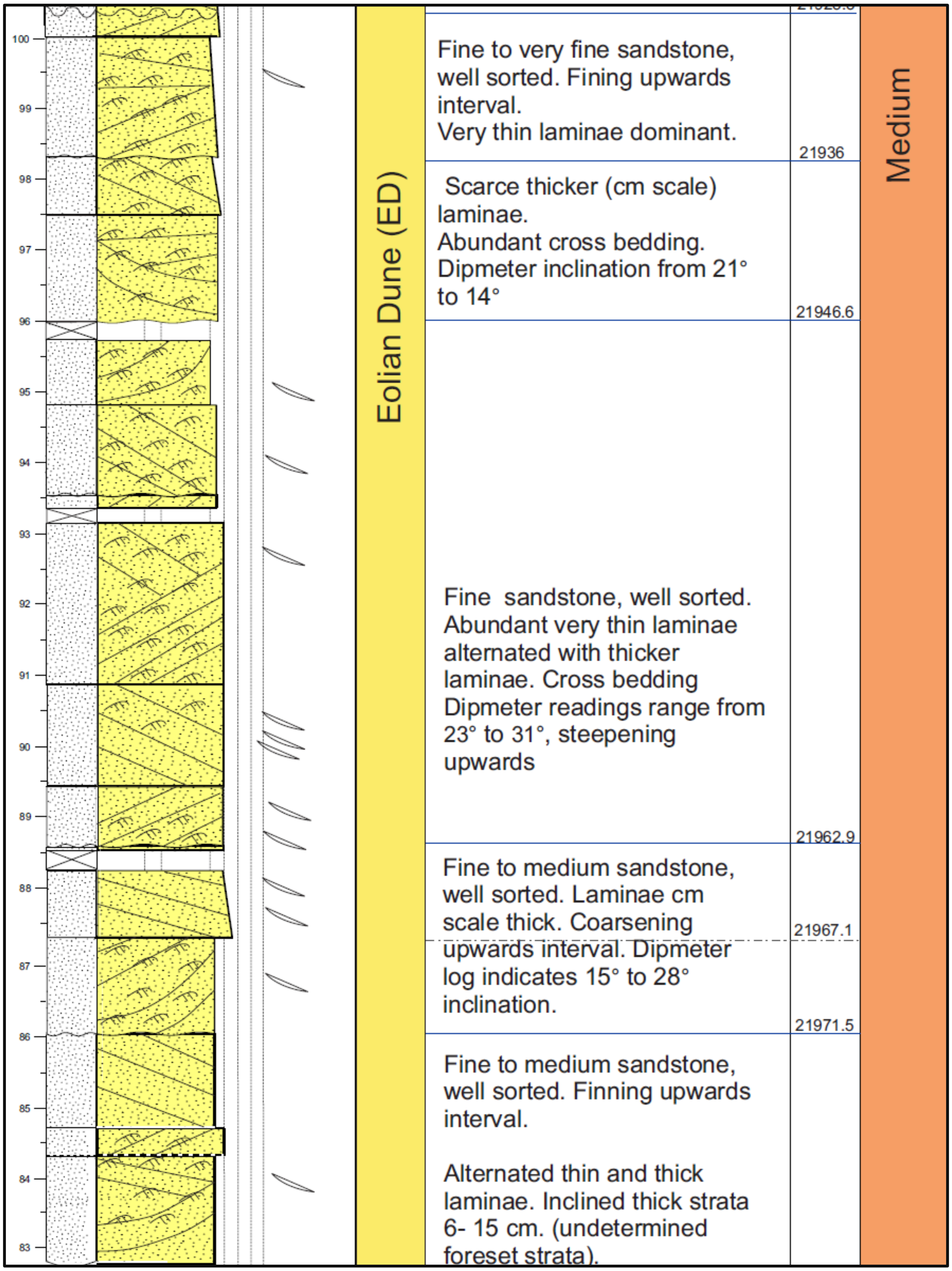

164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
149
148
147
146
Marine
Dark gray to black siltstone.
Scarce thin sand laminae.
Thin lamination (<2 cm) and cross bedding in some intervals
Upper

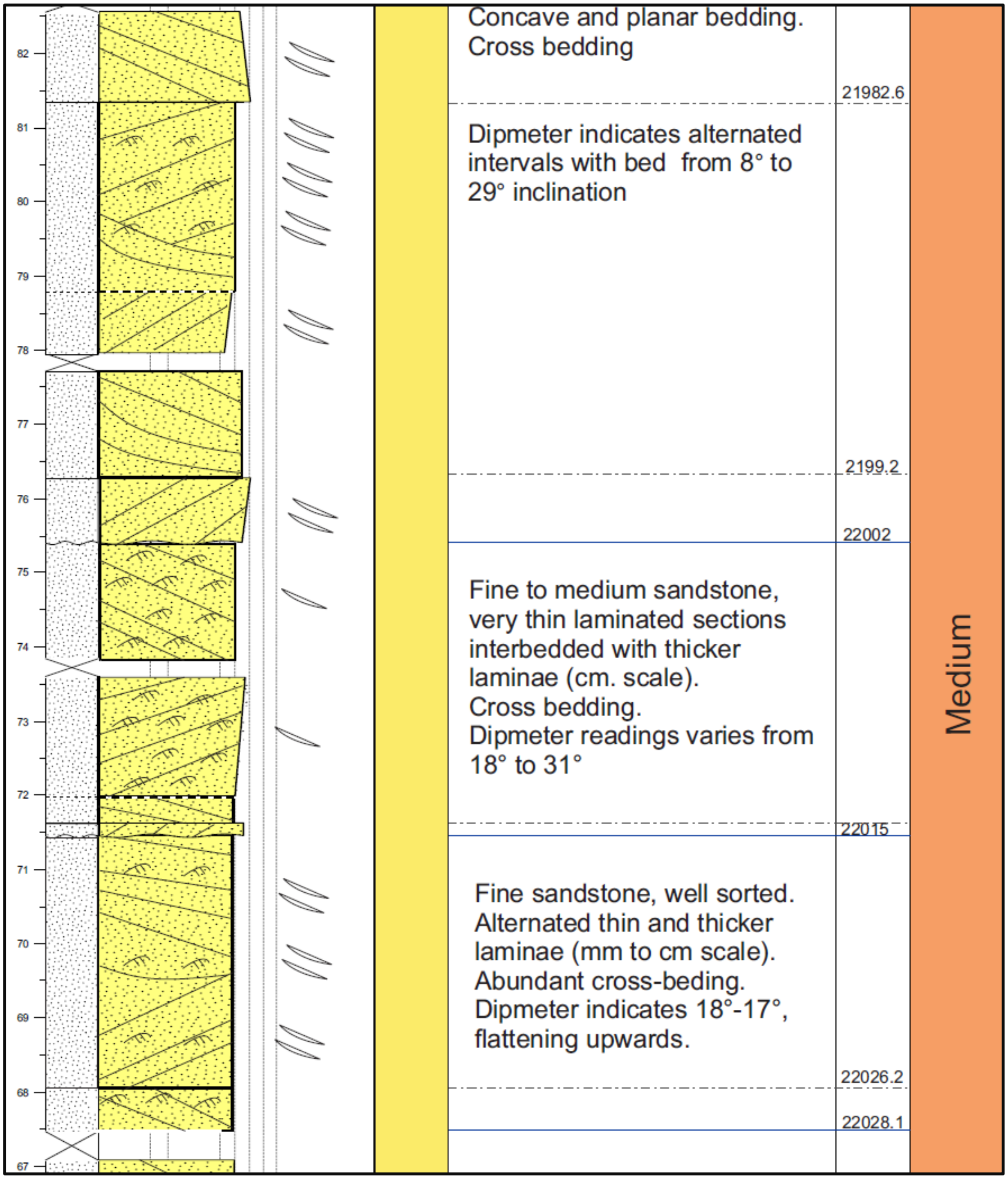

145
144
143
142
141
140
139
138
137
136
135
134
133
132
131
130
129
128
$CaCO_3$
M
M
M
M
Marine
Sandsheets (ES)
Eolian Dune (ED)
21780
Dark gray to black silty sandstones. Very compacted and dense. Carbonate content (effervescent to HCl)
Wavy laminations and concave laminae.
Important change in lithology, coincides with a significant drop in dipping angle from dipmeter log (3°) and upwards it increases up to 5°
21793.4
Thinly laminated sandstone at the base and less laminated upwards
21798.6
Compacted sandstone. Faintly laminated. Sparse cross bedding. High angle foreset strata from dipmeter (21° to 30°)
21803.6
massive sandstone
Light brown sandstone, upper fine to medium grained
Fragmented, bad preserved.
26°- 31° dipping foreset strata (dipmeter measurement)
21817
Very fine to fine sandstone. Massive texture and sparse widely spaced laminae.
Dipmeter indicates high angle bedding (23°-27°)
massive sandstone, very compacted
Very fine to fine sandstone.
Cross bedding , massive with few laminae. Scarce thick laminae (cm scale). Undetermined foreset strata.
21835
Upper
Upper

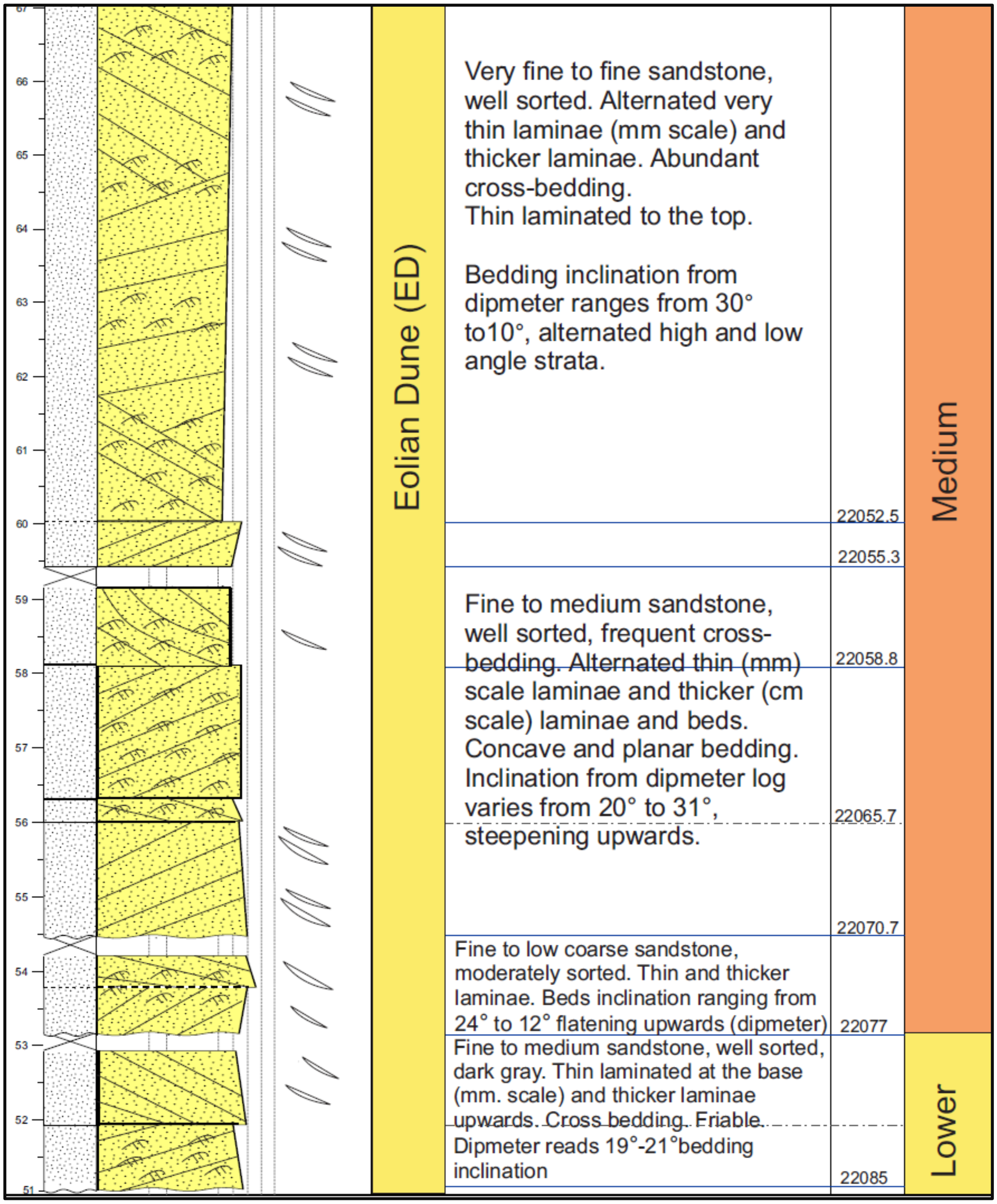

127
126
125
124
123
122
121
120
119
118
117
116
115
M
M
CaCO3
Sandsheets (ES)
Fine to medium grain sandstone. Fragmented- bad preserved. thick laminae (cm scale)
21839
Fine to medium sandstone. Apparent dipping angle steeper than below. Some laminae and massive sandstone towards the top
Foreset inclination ranging from 21° to 30° in this set
21846.2
Thinly laminated sandstone at the base and massive towards the top
21854.2
Change in dip direction. Alternated thin and thicker laminae
Thinly laminated sandstone (pin stripe lamination, mm scale).
Thinly laminated sandstone, pin stripe lamination, mm scale
Dipmeter data indicates bedding angle from 11° to 30°
21870.2
Fine sandstone, alternated thin (mm scale) and thick laminae (cm scale). Bottom: white bands with carbonate material.
21874.2
Upper
Upper

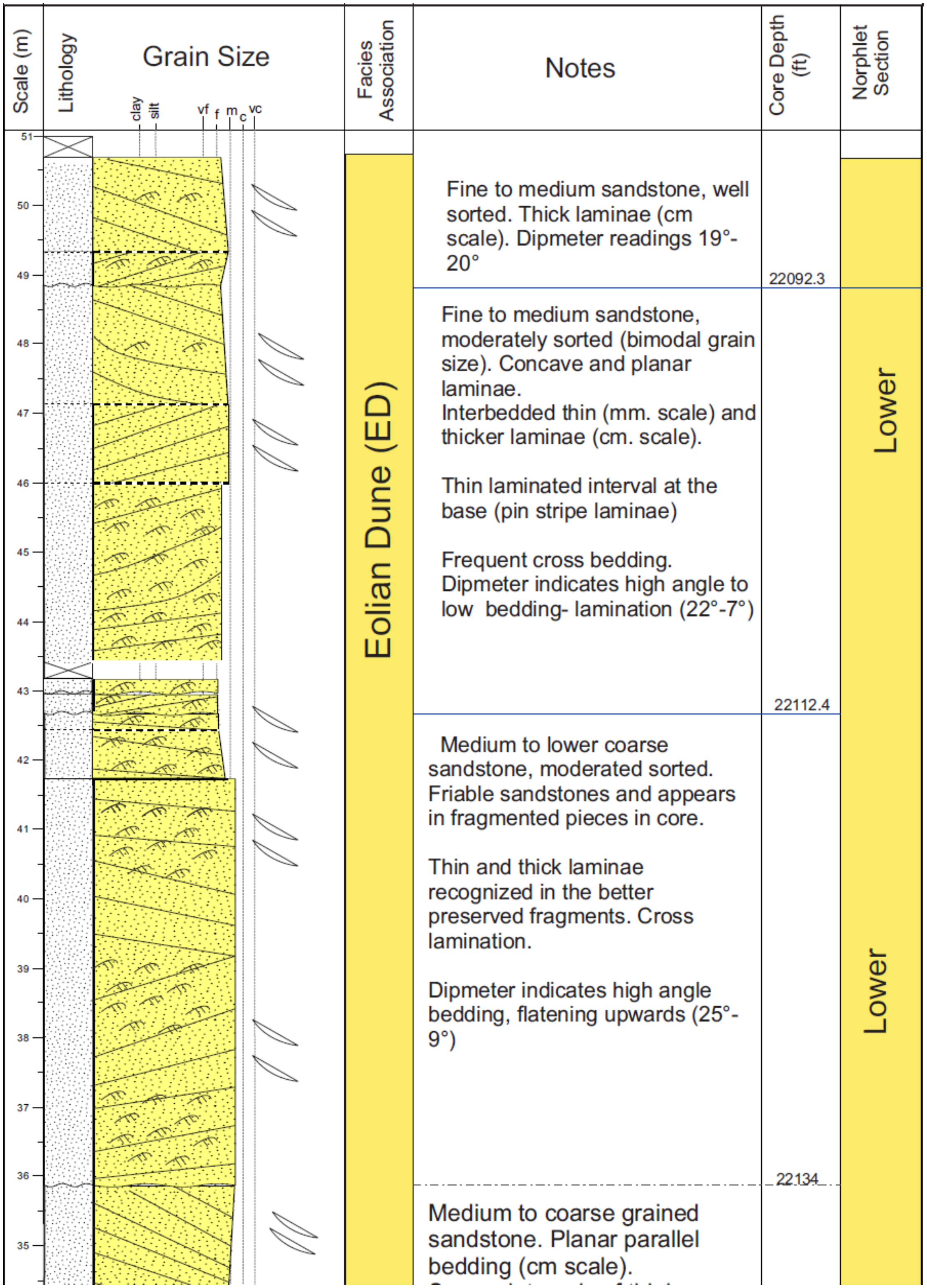


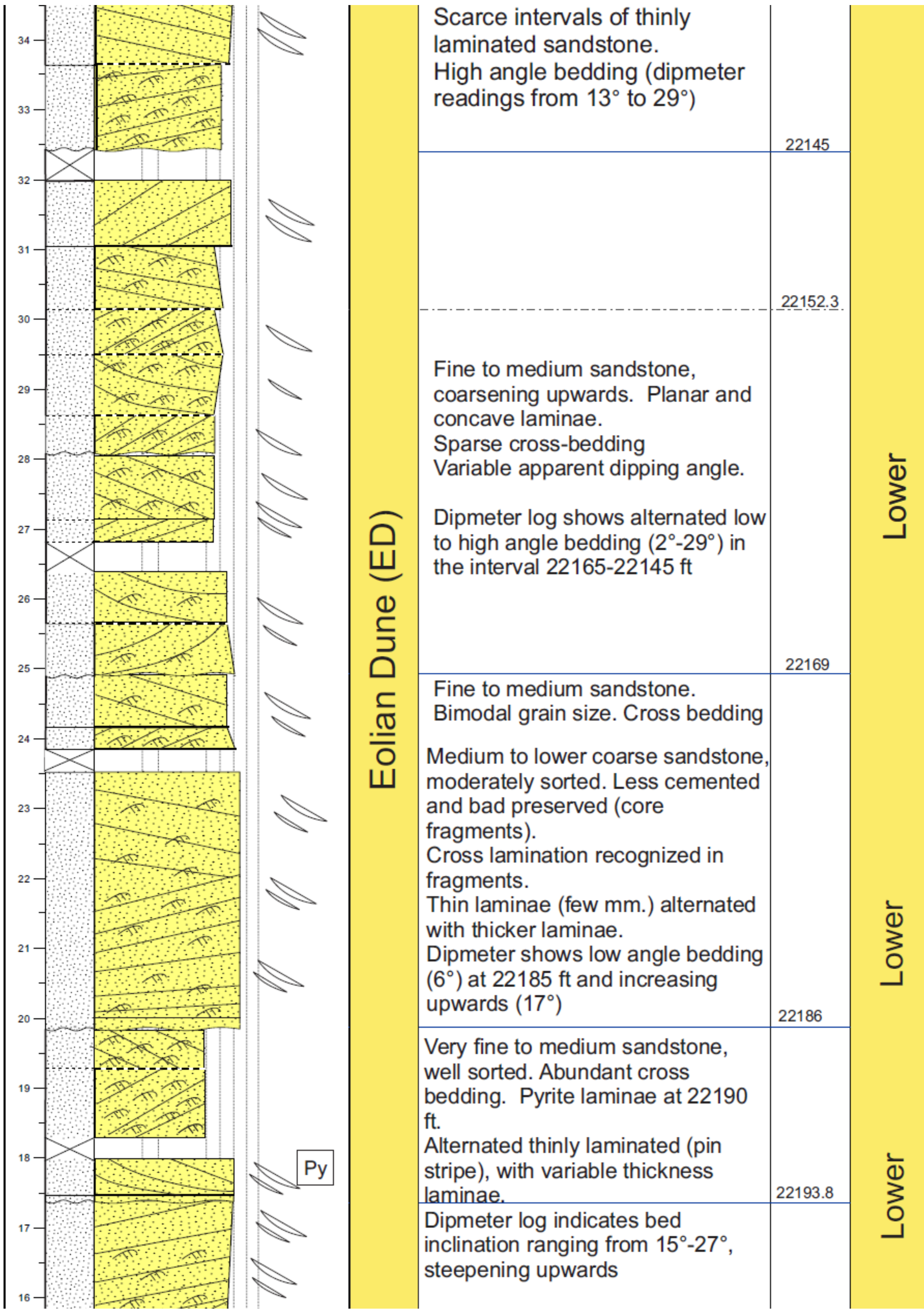
Scale (m)
Lithology
Grain Size
clay
silt
vf
f
m
c
vc
Facies Association
Notes
Core Depth (ft)
Norphlet Section
115
114
113
112
111
110
109
108
107
106
105
104
103
102
101
100
M
M
Sandsheets (ES)
Very fine to fine sandstone. Well sorted. Mainly thinly laminated (mm. scale). Scarce thicker laminae. Basal interval very compact and tight.
Cross lamination within the bed. Concave and planar bedding.
Dipmeter log shows reading from 30° to 10°
21899.5
Very fine to fine sandstone, light gray. Well sorted. Very dense (tight). Very thin laminated intervals alternated with massive sandstone.
Some laminae presents oxidation.
Dipmeter log indicates high angle inclination (30°) alternated with low angle beds (8°).
21928.3
Upper

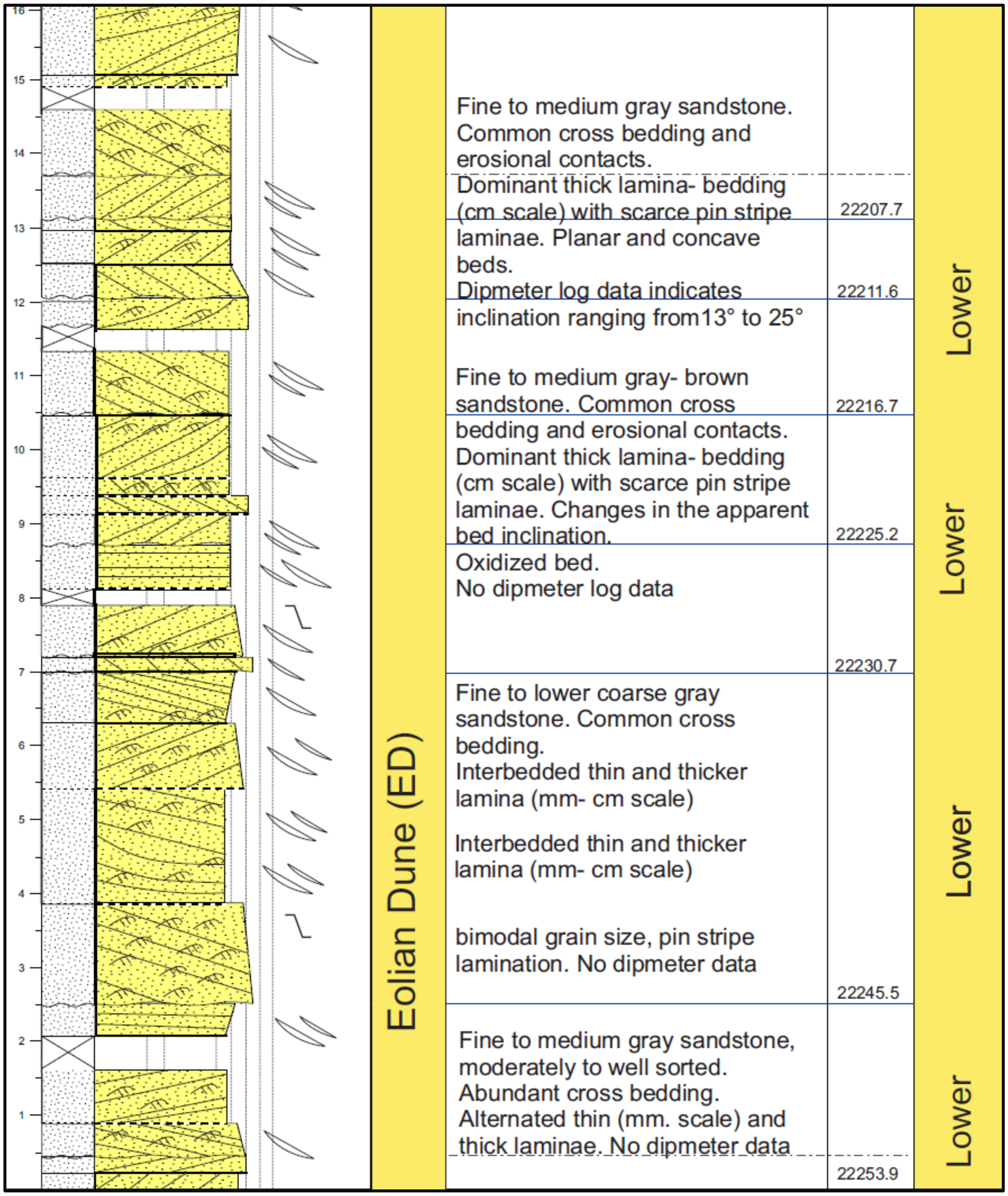

100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
Eolian Dune (ED)
Fine to very fine sandstone, well sorted. Fining upwards interval.
Very thin laminae dominant.
21936
Scarce thicker (cm scale) laminae.
Abundant cross bedding.
Dipmeter inclination from 21° to 14°
21946.6
Fine sandstone, well sorted. Abundant very thin laminae alternated with thicker laminae. Cross bedding Dipmeter readings range from 23° to 31°, steepening upwards
21962.9
Fine to medium sandstone, well sorted. Laminae cm scale thick. Coarsening upwards interval. Dipmeter log indicates 15° to 28° inclination.
21967.1
21971.5
Fine to medium sandstone, well sorted. Finning upwards interval.
Alternated thin and thick laminae. Inclined thick strata 6- 15 cm. (undetermined foreset strata).
Medium


82
81
80
79
78
77
76
75
74
73
72
71
70
69
68
67
Concave and planar bedding.
Cross bedding
21982.6
Dipmeter indicates alternated intervals with bed from 8° to 29° inclination
2199.2
22002
Fine to medium sandstone, very thin laminated sections interbedded with thicker laminae (cm. scale).
Cross bedding.
Dipmeter readings varies from 18° to 31°
22015
Fine sandstone, well sorted.
Alternated thin and thicker laminae (mm to cm scale).
Abundant cross-beding.
Dipmeter indicates 18°-17°, flattening upwards.
22026.2
22028.1
Medium


67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
Eolian Dune (ED)
Very fine to fine sandstone, well sorted. Alternated very thin laminae (mm scale) and thicker laminae. Abundant cross-bedding.
Thin laminated to the top.
Bedding inclination from dipmeter ranges from 30° to10°, alternated high and low angle strata.
22052.5
22055.3
Fine to medium sandstone, well sorted, frequent cross-bedding. Alternated thin (mm) scale laminae and thicker (cm scale) laminae and beds. Concave and planar bedding. Inclination from dipmeter log varies from 20° to 31°, steepening upwards.
22058.8
22065.7
22070.7
Fine to low coarse sandstone, moderately sorted. Thin and thicker laminae. Beds inclination ranging from 24° to 12° flatening upwards (dipmeter)
22077
Fine to medium sandstone, well sorted, dark gray. Thin laminated at the base (mm. scale) and thicker laminae upwards. Cross bedding. Friable.
Dipmeter reads 19°-21°bedding inclination
22085
Medium
Lower


Scale (m)
Lithology
Grain Size
clay
silt
vf
f
m
c
vc
Facies Association
Notes
Core Depth (ft)
Norphlet Section
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
Eolian Dune (ED)
Fine to medium sandstone, well sorted. Thick laminae (cm scale). Dipmeter readings 19°-20°
22092.3
Fine to medium sandstone, moderately sorted (bimodal grain size). Concave and planar laminae.
Interbedded thin (mm. scale) and thicker laminae (cm. scale).
Thin laminated interval at the base (pin stripe laminae)
Frequent cross bedding.
Dipmeter indicates high angle to low bedding- lamination (22°-7°)
22112.4
Medium to lower coarse sandstone, moderated sorted. Friable sandstones and appears in fragmented pieces in core.
Thin and thick laminae recognized in the better preserved fragments. Cross lamination.
Dipmeter indicates high angle bedding, flatening upwards (25°-9°)
22134
Medium to coarse grained sandstone. Planar parallel bedding (cm scale).
Lower
Lower


34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
Py
Eolian Dune (ED)
Scarce intervals of thinly laminated sandstone.
High angle bedding (dipmeter readings from 13° to 29°)
22145
22152.3
Fine to medium sandstone, coarsening upwards. Planar and concave laminae.
Sparse cross-bedding
Variable apparent dipping angle.
Dipmeter log shows alternated low to high angle bedding (2°-29°) in the interval 22165-22145 ft
22169
Fine to medium sandstone.
Bimodal grain size. Cross bedding
Medium to lower coarse sandstone, moderately sorted. Less cemented and bad preserved (core fragments).
Cross lamination recognized in fragments.
Thin laminae (few mm.) alternated with thicker laminae.
Dipmeter shows low angle bedding (6°) at 22185 ft and increasing upwards (17°)
22186
Very fine to medium sandstone, well sorted. Abundant cross bedding. Pyrite laminae at 22190 ft.
Alternated thinly laminated (pin stripe), with variable thickness laminae.
22193.8
Dipmeter log indicates bed inclination ranging from 15°-27°, steepening upwards
Lower
Lower
Lower


16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Eolian Dune (ED)
Fine to medium gray sandstone.
Common cross bedding and
erosional contacts.
Dominant thick lamina- bedding
(cm scale) with scarce pin stripe
laminae. Planar and concave
beds.
Dipmeter log data indicates
inclination ranging from13° to 25°
Fine to medium gray- brown
sandstone. Common cross
bedding and erosional contacts.
Dominant thick lamina- bedding
(cm scale) with scarce pin stripe
laminae. Changes in the apparent
bed inclination.
Oxidized bed.
No dipmeter log data
Fine to lower coarse gray
sandstone. Common cross
bedding.
Interbedded thin and thicker
lamina (mm- cm scale)
Interbedded thin and thicker
lamina (mm- cm scale)
bimodal grain size, pin stripe
lamination. No dipmeter data
Fine to medium gray sandstone,
moderately to well sorted.
Abundant cross bedding.
Alternated thin (mm. scale) and
thick laminae. No dipmeter data
22207.7
22211.6
22216.7
22225.2
22230.7
22245.5
22253.9
Lower
Lower
Lower
Lower